PRELIMINARY ANALYSIS FOR LUNAR ROVING VEHICLE STUDY GROUND DATA SYSTEMS AND OPERATIONS

JPL CONTRACT NO. 952668

VOLUME I OF III

ROVING VEHICLE GUIDANCE

(REMOTE DRIVING STUDY)

HUGHES

HUGHES AIRCRAFT COMPANY
SPACE SYSTEMS DIVISION

30 JUNE 1970

HUGHES REFERENCE NO. C0077

VOLUME I OF III

ROVING VEHICLE GUIDANCE

(REMOTE DRIVING STUDY)

PRELIMINARY ANALYSIS FOR LUNAR ROVING VEHICLE STUDY GROUND DATA SYSTEMS AND OPERATIONS

JPL CONTRACT NO. 952668

JUN 3 0 1970

HUGHES

HUGHES AIRCRAFT COMPANY
SPACE SYSTEMS DIVISION

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

CONTENTS

CONTENTS (Continued)

SUMMARY

The study contract for preliminary analysis for Lunar Roving Vehicle (LRV) Ground Data Systems (GDS) and Operations was initiated in September 1969, and was originally intended as a six-month task. During February 1970, Hughes was directed to stretch out the existing program with a Final Report delivery scheduled for 30 June 1970.

The content of the Final Report (Volumes I, II, and III) constitutes only part of the final product by the Hughes Aircraft Company in res ponse to Contract No. 952668. The total response is listed below and it should be noted that material printed in Jet Propulsion Laboratory documents was supplied under the terms of the contract in final draft form.

- Preliminary Analysis for Lunar Roving Vehicle Study – Ground Data Systems and Operations, Hughes Reference No. C0077, dated 30 June 1970: Volume I, Roving Vehicle Guidance (Remote Driving Study); Volume II, Roving Vehicle Payload (Science Mode Time Analyses); Volume III, Roving Vehicle Navigation (Evaluation Determination Analyses).

- LRV Navigation and Guidance System Phase A Study Report, JPL Document No. 760-42, dated 15 October 1969: Section V, Mission Operations; Section VI, Navigation and Guidance Operations; Section VII, Problem Areas; Section X, Plan for Phase B Study.

- Science Ground Data System and Science Operations Organization for Remotely Controlled Lunar Traverses – Phase A Study Report, JPL Document No. 760-39, dated 10 October 1969: Section VI, Science Operations; Section VII, Problem Areas, Section X, Phase B Study Plan.

- Operations Profiles for Lunar Roving Missions, JPL Document No. 760-46, dated May 1970.

Originally, it was not planned for Hughes to participate in Phase A Report preparation. The basic responsibility of Hughes in the early part of this contract had been to assist JPL in defining all mission-dependent Earth activities and resources (hereinafter referred to as the "Mission Operations Complex" – MOC) required to support the remote-controlled phase of the

LRV Mission. Since this constituted a variable which is dependent upon mission requirements, the total plan which implemented these requirements was first established.

Mission requirements also dictate a general LRV design. Such a design is not necessary in defining a general MOC but becomes necessary in establishing its details (commensurate to the extent of available LRV design detail). No sole LRV design existed throughout the contract period. Bendix and Grumman each had several designs in the early part of the period and JPL therefore postulated a single design to act as a baseline for the Hughes effort of MOC definition. Considerable time was spent coordinating with JPL sources regarding establishing and periodically up-dating a postulated LRV design without incompatibilities and with a level of detail useful toward MOC definition. Continuing assistance to JPL was provided in assessing the effect on the GDS baseline design of the LRV mission, vehicle, and science payload changes during the study, and design change recommendations were made as appropriate.

It was originally intended to deliver to JPL detailed definition of the Ground Data System in the areas of display, operations profile, operations organization, navigation programs and computer applications, hazard prediction programs, and avoidance maneuver techniques. During January and February of 1970, it was determined by JPL that the study should concentrate more in the areas of 1) remote driving problems, 2) Navigational analyses for operations use (concentrating on elevation determinations), and 3) time line analyses. In particular, it was decided to develop the above definitions to only the intermediate level and not initiate work on a general command and control computer program, or identify a single operations organization. It has also been intended to expand the detail of the MOC to a level of detail attainable within the remainder of the contract period. However, this effort was also suspended at JPL's request. Thus, during January and February of 1970, a report entitled "MOC Definition for Synthesized LRV Design" was submitted. This report consisted of five basic sections plus an appendix; and included an Introduction, Synthesized LRV Description, Operations Profile, and MOC Profiles. This material was used by JPL in preparing the Phase B Report.

The MOC profile charts in the Phase B Report show the direct correlation of all the particular Earth-based activities and equipment used to implement each specific operational activity identified by numerical subdivision of a basic operation "mode" (the first divisional level within the remote controlled phase of the mission). The estimated Delta time to accomplish each row of the MOC charts was also calculated. An iteration with specific operational activities and general mission plans is required to establish total mission time lines. This was not pursued further in the areas of Guidance and Navigation by Hughes at JPL's request.

Paralleling the above in time was an effort by Hughes to identify (for operational use) the subtle aspects of perhaps the most demanding of the LRV mission requirements--Navigation and Guidance. A review was made of all available documentation produced by Bendix, General Motors, and Grumman regarding the subject. Preliminary investigation in Navigation by landmark showed that accuracy versus number of visual landmarks, and accuracy versus number of navigation updates for a given course, was not a simple relationship. Subsequent investigations established appreciably reliable criteria for operational decisions when navigating by landmark.

Volume I details considerations applicable to aid remote driving by superimposing driving aids on the TV panorama. These aids are used by the Remote Driver at the Remote Controller Position while the vehicle is in motion. The vehicle general design baseline is first established.

Volume II contains four detailed time line studies of portions of the Stationary Science Mode. These studies provide an additional link in the continuing iterative process of defining the LRV mission operations procedure, ground equipment, and administrative organization.

Volume III is mainly concerned with elevation determination. Some early unfinished work on Rover Navigation is also presented. Preliminary error curves of Rover position as affected by landmark orientation with respect to LRV path are shown; also, a table representing a partial comparison of various navigation schemes is included. The elevation determination methods considered are 1) use of the basic LRV instruments, 2) addition of a ranging Laser and precision inclinometer, 3) tracking an orbiter from the Rover, and 4) miscellaneous techniques including a stable platform, on e or more star trackers, a sun seeker, gyrocompassing, Foucauld pendulum, and differential ranging. The intent of the volume is to provide sufficient information concerning a variety of navigation and elevation determination methods to permit filtering out of less attractive schemes.

PREFACE

The beginning portion of the "Remote Driving Problem" Study (Section II), was directed toward establishing a vehicle general design based on Remote Driving operational requirements imposed on the complete Mission System (i. e., the vehicle, its communication links with the remote controller station, and the remote controller station). The vehicle baseline design itself is summarized in Section III of this study. Section IV is devoted to a specific aspect of the Remote Controller Station intended to aid Remote Driving by superimposing Driving aids (e. g. predicted vehicle path, range lines, crevasse hazard detection lines) on the TV panorama (of the view in front of the vehicle) used by the Remote Driver while the vehicle is in motion.

GUIDANCE

BACKGROUND

I. Phase A Contributions

Preliminary functional requirements for LRV guidance and control were reviewed by Hughes Aircraft Company. Hughes-recommended ground data system functional guidance and control requirements and operations organization were included in the formal issue of Jet Propulsion Laboratory Document Number 760-42, entitled "LRV Navigation and Guidance System Phase A Study Report," dated 15 October 1969, Sections V and VI. Functions of the ground data system were organized into two main categories in that report, i. e. , navigation and guidance. Functional diagrams were generated reflecting this organization, and functional descriptions were prepared which described in detail the various activities identified in the functional diagrams. This was accomplished for the four candidate systems.

Jet Propulsion Laboratory Document Number 760-42 also included Hughes-recommended Phase B Study Plan (Section X) and Problem Areas (Section VII) anticipated by Hughes for the Phase B study effort.

II. Phase B Contributions

A summary chart of the Bendix and Grumman candidate vehicles was prepared in regard to the navigation and guidance concepts. A single navigation/guidance baseline was then jointly established by Jet Propulsion Laboratory and Hughes Aircraft Company personnel. This integrated GDS functional baseline design was used to establish a corresponding navigation/ guidance operations profile and the navigation/guidance GDS concept.

The feasibility of manual, semi-automatic, and automatic LRV course and obstacle avoidance maneuver techniques was studied using available navigation, obstacle detection, image, and lunar environment data.

Preliminary and intermediate ground data systems and operations profile for navigation/guidance were established. The task was approached by preparing functional flow block diagrams describing the minor sequence in the two navigation and guidance modes: the navigation and guidance stop (navigation update) mode and the traverse mode. The MOC profile was further detailed to include information processing, information display, and corresponding human activity requirements for the navigation/guidance areas.

During January and February 1970, the above material was detailed and submitted in near final form and published essentially in its entirety as the Jet Propulsion Laboratory Phase B Interim Study Report ("Operations Profiles for Lunar Roving Missions," Jet Propulsion Laboratory Document Number 760-46, dated May 1970) to the National Aeronautics and Space Agency. Also, during January 1970, the guidance and control task was directed into a study of remote driving problems (next section).

REMOTE DRIVING PROBLEM

I. Summary

The beginning portion of the Remote Driving Problem Study (Section II) was directed toward establishing a vehicle general design based on remote driving operational requirements imposed on the complete mission system, i.e., the vehicle, its communication links with the remote controller station, and the remote controller station. The vehicle baseline design itself is summarized in Section III of this study. Section IV is devoted to a specific aspect of the remote controller station intended to aid remote driving by superimposing driving aids, e.g., predicted vehicle path, range lines, crevasse hazard detection lines, on the TV panorama (of the view in front of the vehicle) used by the remote driver while the vehicle is in motion.

II. Vehicle General Design Considerations for Vehicle Remote Guidance

A. Obstacle Detection

1. General

The total system time delay for obstacle detection and vehicle response is:

$$T = t_D + t_R$$

where t_D = display time = period between sensing of the obstacle by the LRV and display of the obstacle on the earth, either visually or alphanumerically.

t_R = reaction time = period between sensing of the display by the remote driver and actual change in direction or velocity of the LRV.

It is assumed that:

$$t_D \begin{cases} = 6 \text{ seconds [TV]} \\ \cong 1.3 \text{ seconds [engineering telemetry]} \end{cases}$$

$$t_R = 4 \text{ seconds}$$

2. TV

The significant requirements associated with TV utilized as an obstacle detection device are:

a) Sufficiently stable moon-earth communications link margin in the face of vehicle motion so as to accommodate continuously undistorted video.

b) Upper limit on frame transmission rate so as to minimize moon-earth communications bandwidth requirements.

c) Lower limit on frame transmission rate to minimize required reaction time.

d) Adequate resolution.

e) Adequate contrast.

f) Advantageous location of the LRV camera and maximum vehicle velocity.

g) Short exposure time (to avoid picture smear due to vehicle motion) and adequate field-of-view.

h) Minimization of scene jitter due to unstabilized platform mounting of TV camera.

The following discusses these topics further:

a) Stable Link Margin. It is assumed that an RF carrier frequency in the S-band range (2 to 3 GHz) will be used on an LRV mission. Also, it is assumed that an antenna of sufficient directionality and pointability will be onboard the LRV.

b) Upper Limit on Frame Rate. The assumed link carrier frequency range imposes an upper limit for the TV frame rate on the order of 3 to 6 frames per second maximum, assuming use of an LRV transmitter, receiver, and antenna of capability similar to that on Surveyor. A higher frame rate is not usable while moving due to scene jitter, unless the camera were mounted on a stable platform during vehicle motion. Also, a higher frame rate may not be necessary for the order of magnitude velocity (3 km/hr maximum) considered as a safe limit for traversing unknown and rough lu:rain via remote driving. (Reference Appendix A, Item 5.)

At 4 km/hr, the vehicle travels 1.11 m/sec. Assuming obstacle detection and avoidance time T = 10 seconds, an obstacle would have to be detected via TV no closer in range (hereafter referred to as R_c = critical detection range) than 10 x 1.11 = 11.1 meters ahead of the LRV in order to stop the vehicle before LRV/obstacle contact is made. This assumes no additional delay due to low TV frame rate. If the rate were 5 frames per

per second, i. e., a frame time of 0. 2 second, one frame time would represent 5 per cent of T; for 20 frames per second rate, one frame time (0. 05 seconds) would represent 1/2 per cent of T. The difference in time is small, but the price difference to accommodate the higher frame rate from communications, power, and thermal viewpoints is huge for an S-band carrier frequency. Therefore, 5 frames per second shall be used as an adequate upper limit on TV frame rate for obstacle detection considering these limitations.

c) Lower Limit on Frame Rate. A low frame rate ($\leq$ 1 frame per second) has the advantage in minimizing scene jitter over rough lurain without the need for a stable platform camera mount. The disadvantages, of course, are the scene discontinuity and the increase in obstacle detection time (t_D).

d) Adequate Resolution. The minimum mobility requirements for the LRV as stated in the Phase A Study Report (Appendix A, Reference 1) include capability to negotiate a step obstacle $\leq$ 1 meter and a crevasse obstacle $\leq$ 70 cm for one wheel. Camera resolution adequate to recognize these obstacles adequately is significantly coarser than landmark navigation requirements where accuracy in landmark bearing and elevation measurements is paramount. It will be assumed that the camera resolution is 0. 1 degree or better for the purpose of landmark navigation.

e) Adequate Contrast. The greater the intensity of a signal, the faster will be the human reaction time, up to some limiting value as shown in Figure 1 (Appendix A, Reference 3). This is interpreted to apply to relative intensity, i. e., contrast, as well as absolute intensity. Therefore, for the purpose of minimizing reaction time, it is apparent that a degree of picture contrast just to the right of the knee of the curve in Figure 1 is adequate.

f) Advantageous Location of the LRV Camera and Maximum LRV Velocity. Maximum LRV velocity may be established by the criteria of being able to recognize an obstacle of hazardous size at a distance sufficient to permit enough time to stop the vehicle in a remote driving mode, i. e., with the assumed 10 second system delay in the loop.

Assume a crevasse of hazardous size for one wheel, i. e., there may be insufficient torque to drive the vehicle wheel out of the crevasse, is $\geq$ 0. 7 meter. This may represent a crater $\geq$ 0. 7 meter in diameter or it may be a $\geq$ 0. 7 meter wide rill.

Assume also that a crevasse must subtend a minimum of 1 degree vertical field-of-view to be properly recognized as being hazardous in size. Figure 2 shows the above geometry. From Figure 2:

$$\tan \alpha = \frac{D_{cw} + D_s}{C_H} \qquad (1)$$

$$\tan (\alpha + 1 \text{ degree}) = \frac{D_{cw} + D_s + 0.7}{C_H} = \frac{\tan \alpha + \tan (1 \text{ degree})}{1 - \tan \alpha \tan (1 \text{ degree})} \qquad (2)$$

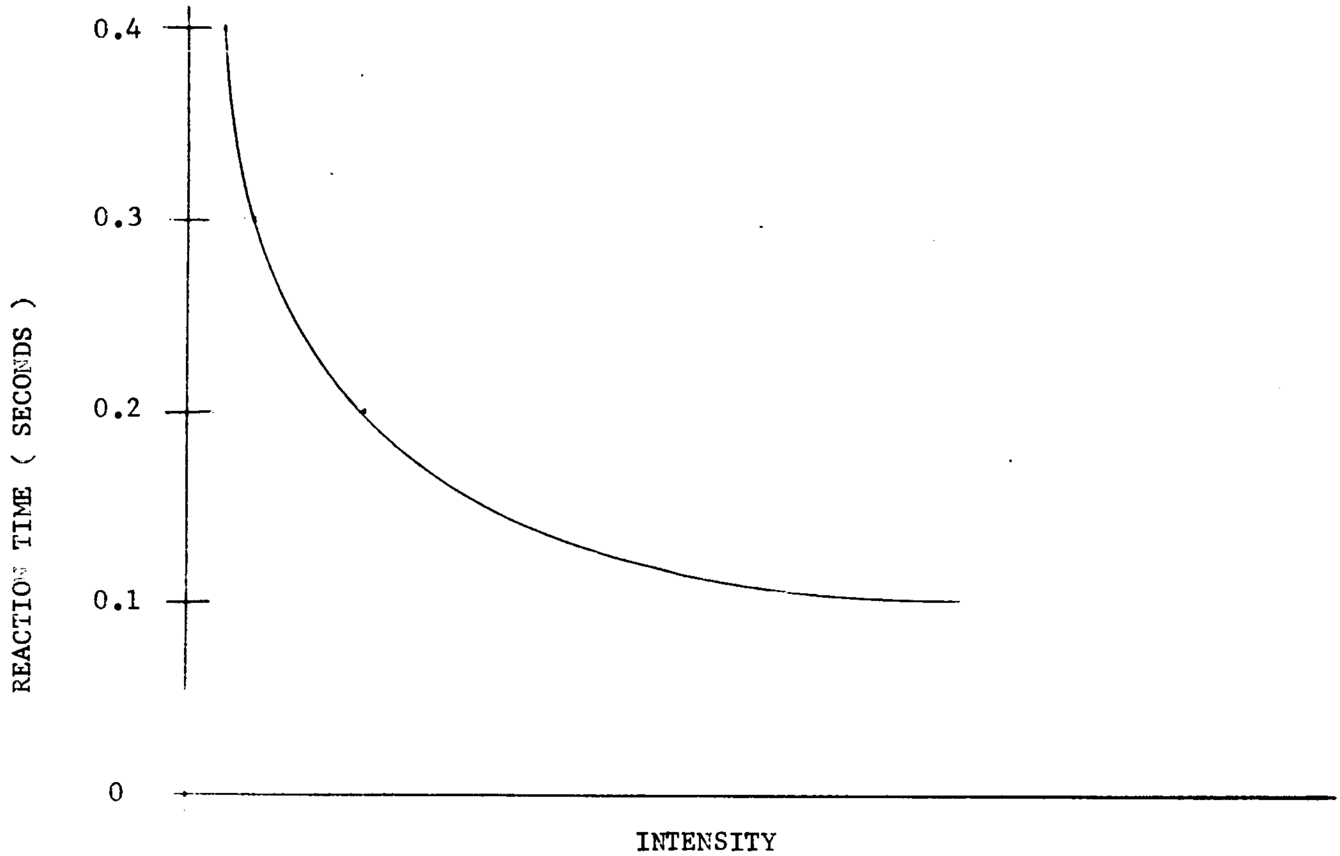


Figure 1. Limiting Characteristic of Human Reaction Time Versus Light Intensity of Perceived Signal

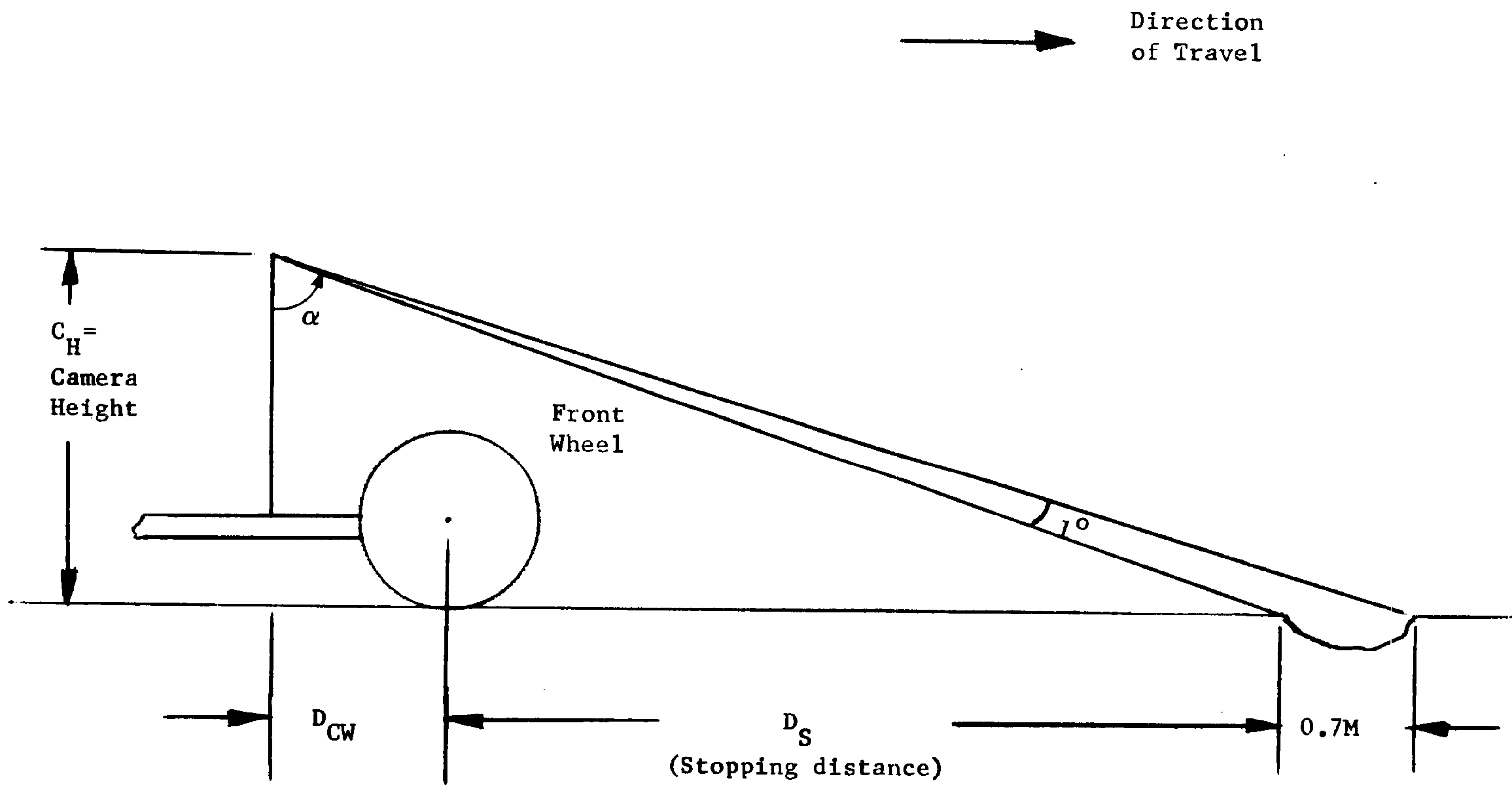


Figure 2. Geometric Relations Conforming to Assumptions Regarding Detection of Minimum Size Hazardous Crevasse

Substituting (1) into (2) and solving for C_H:

$$C_H = \frac{0.7 \pm \sqrt{0.49 - 4\,[\tan 1\ \text{degree}]^2\,[D_{cw} + D_s + 0.7]\,[D_{cw} + D_s]}}{2 \tan 1\ \text{degree}} \qquad (3)$$

Table 1 shows a calculated value of maximum velocity corresponding to an assumed camera height, the stopping distance (D_s) corresponding to 10 seconds of travel at the calculated velocity, and assumed values for the distance between camera surface subpoint and front wheels center surface subpoint (D_{cw}). It is assumed that actual vehicle reaction time to come to a halt is negligible compared to the 10 second system delay. It is apparent that the higher and more forward the camera is mounted, the higher is the maximum permissible velocity. Mechanical limitations of vibration of the camera on a long mast (akin to an inverted pendulous bob) due to rough terrain, and the likelihood of a maximum vehicle width in the neighborhood of 2 meters, prompts a selection of 2 meters as a practical value of camera height. This automatically bounds the maximum vehicle velocity to approximately 2.5 km/hr, as seen in the table.

One point that the above treatment has neglected, but which warrants attention, is that of ambiguity of crevasse detection due to shadowing. TV detection of a prominence, especially of 1 meter step size, is a negligible problem in comparison to TV detection of a crevasse 70 cm across. Shadows due to small prominences or irregular lurain may be misinterpreted as being due to a crevasse or vice versa. On the other hand, lack of any significant shadowing would increase the chance of misinterpretation. Visual detection of crevasses will be inconclusive unless numerous stops are made so that sufficient time is allowed to examine in detail each potential crevasse before critical encounter.

g) Short Exposure Time and Adequate Field-of-View. Both of these TV parameters may be bounded by a criteria for picture smear. Picture smear in one scene element is defined as the apparent percent shift, either vertically or horizontally, of that scene element during the exposure period. Assume that a scene element is 0.1 degree x 0.1 degree.

There is an inherent picture smear generated (as the vehicle moves) which is independent of surface roughness. That is to say, even if the vehicle were traveling on a perfectly flat surface and there was no mechanical vibration of the camera viewing axes during motion, a picture smear will still be generated due to the apparent shift of a scene element on the flat surface during the exposure time.

In Figure 3, FRONT, TOP, and SIDE views of one "slice" of the camera FOV and its intersection with a flat lunar surface are shown for two positions of the camera separated by a surface distance traveled = x meters. At t_o, the start of the camera exposure period, one picture element is viewing point P_o. At the end of the exposure period, that same scene element is viewing point P_1, which is a flat surface distance x meters ahead of point P_o in the direction of travel.

TABLE 1

CAMHT 12:45 WED. 05/27/70

VELØCITY [KM/HR]	D_S IN 10 SEC [METERS]	DCW [METERS]	CAM HEIGHT [METERS]
.83729	2.32581	.5	.25
.65729	1.82581	1	.25
.47729	1.32581	1.5	.25
1.30091	3.61363	.5	.5
1.12091	3.11363	1	.5
.940907	2.61363	1.5	.5
1.65384	4.59401	.5	.75
1.47384	4.09401	1	.75
1.29384	3.59401	1.5	.75
1.94869	5.41302	.5	1
1.76869	4.91302	1	1
1.58869	4.41302	1.5	1
2.20598	6.12773	.5	1.25
2.02598	5.62773	1	1.25
1.84598	5.12773	1.5	1.25
2.43632	6.76754	.5	1.5
2.25632	6.26754	1	1.5
2.07632	5.76754	1.5	1.5
2.646	7.35001	.5	1.75
2.466	6.85001	1	1.75
2.286	6.35001	1.5	1.75
2.83918	7.88662	.5	2
2.65918	7.38662	1	2
2.47918	6.88662	1.5	2
3.01873	8.38535	.5	2.25
2.83873	7.88535	1	2.25
2.65873	7.38535	1.5	2.25
3.18674	8.85206	.5	2.5
3.00674	8.35206	1	2.5
2.82674	7.85206	1.5	2.5
3.34482	9.29116	.5	2.75
3.16482	8.79116	1	2.75
2.98482	8.29116	1.5	2.75
3.4942	9.70611	.5	3
3.3142	9.20611	1	3
3.1342	8.70611	1.5	3

TABLE 1. (Continued)

```
CAMHT      12:48   WED.   05/27/70

10 P=3.14159265/180
20 S=TAN(1*P)
60 PRINT"VELØCITY","D IN 10 SEC","DCW","CAM HEIGHT"
70 PRINT"(KM/HR)","(METERS)","(METERS)","(METERS)"
73 FØR J=1 TØ 12
74 C=J/4
76 FØR K=1 TØ 3
80F1=SQR((0.49)-(4*((((-0.7)/S)*C)+(C↑2))))
85 D1=(-0.7+(F1))/2
90 D2=(D1)-(K/2)
100 V=((D2)*3.6E3)/1E4
110 PRINT V,D2,K/2,C
120 NEXT K
130 NEXT J
200 END
```

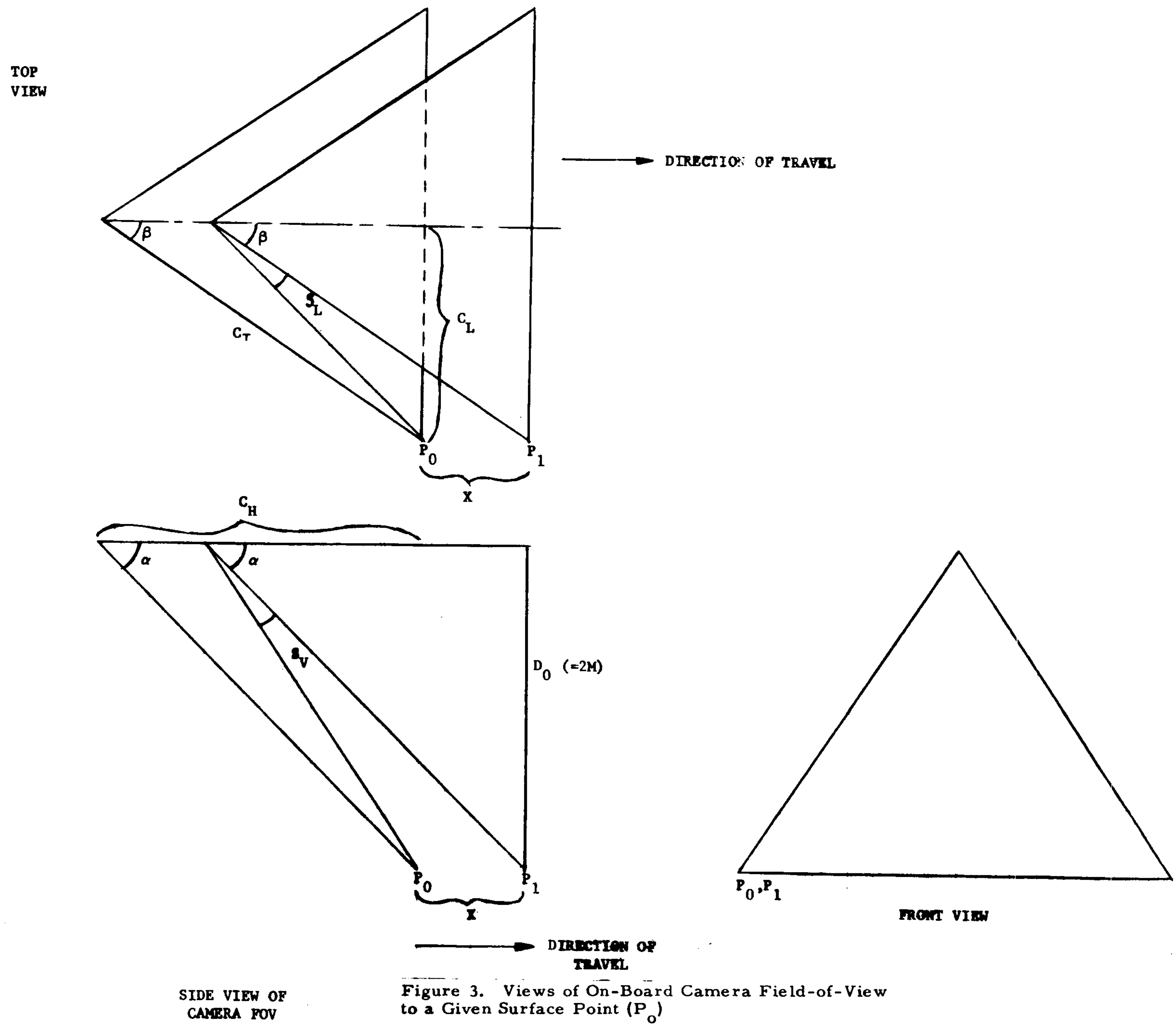


Figure 3. Views of On-Board Camera Field-of-View to a Given Surface Point (P_o)

The picture element in discussion has angular coordinates (γ, β), i.e., it is of the element seen by the camera γ degrees down and β degrees to the right from a horizontal line of sight.

S_V = Change in vertical viewing angle to point P_o during the exposure period.

S_L = Change in lateral viewing angle to point P_o during the exposure period.

D_O = Height of camera focal point above the surface.

Relations from Figure 3:

$$\sqrt{C_H^2 + C_L^2} = C_T \tag{4}$$

$$\sqrt{C_T^2 + D_O^2} = C_O = \text{Distance from camera to lunar surface} \tag{5}$$

$$\tan \beta = \frac{C_L}{C_H} \tag{6}$$

$$\tan \gamma = \frac{D_O}{C_H} \tag{7}$$

$$\tan (\beta + S_L) = \frac{C_L}{C_H - x} \tag{8}$$

$$\tan (\gamma + S_V) = \frac{D_O}{C_H - x} \tag{9}$$

$$\frac{x}{v} = T = \text{exposure time, where } v = \text{velocity} \tag{10}$$

Solving for x in (8) and substituting (6) and (7) into results:

$$x = \left(\frac{D_O}{\tan \gamma}\right)\left[1 - \frac{\tan \beta}{\tan (\beta + S_L)}\right] \tag{11}$$

Substituting (11) into (10) and solving for $\tan S_L$:

$$\tan S_L = \frac{vT \tan \gamma \tan \beta}{D_O (\tan^2 \beta + 1) - vT \tan \gamma} \tag{12}$$

Solving for x in (9) and substituting (7) into results:

$$x = D_O \left[\frac{1}{\tan \gamma} - \frac{1}{\tan (\gamma + S_V)} \right] \tag{13}$$

Substituting (13) into (10) and solving for tan S_V:

$$\tan S_V = \frac{vT \tan^2 \gamma}{D_O [\tan^2 \gamma + 1] - vT \tan\gamma} \tag{14}$$

Appendix B is a computer run using Equations (12) and (14) for the following assumed parameters:

Vehicle velocity = 1 km/hr
Camera focal point height = 2 meters
Exposure time = 10 ms
Picture element size = 0.10 degree of arc

The percent shifts were obtained simply by:

$$\text{per cent vertical shift} = \frac{S_V \times 100 \text{ per cent}}{0.1 \text{ degree}} \tag{15}$$

$$\text{per cent lateral shift} = \frac{S_L \times 100 \text{ per cent}}{0.1 \text{ degree}} \tag{16}$$

If a criteria of 20 per cent maximum shift, either vertically or laterally, is used, then the run indicates that the lower bound on the vertical FOV is 31 degrees down from a horizontal line-of-sight. Correspondingly, the maximum HFOV is confined to 60 degrees total.

The assumed vehicle velocity of 1 km/hr is representative as an average; 1/2 km/hr is more likely over rough lurain, and 2 km/hr is more likely over very smooth lurain. The upper bound on the VFOV may be established as follows:

It would be required to keep the horizon and distant landmarks in view for driver orientation in traversal. The distance to the horizon on the moon from a 2 meter high viewing point is (refer to Figure 4):

$$D = \sqrt{(R + h)^2 - R^2} = \sqrt{2Rh + h^2} \cong 2.64 \text{ km}$$

where R = radius of the moon = 1.738×10^6 meters

h = height above lunar surface = 2 meters

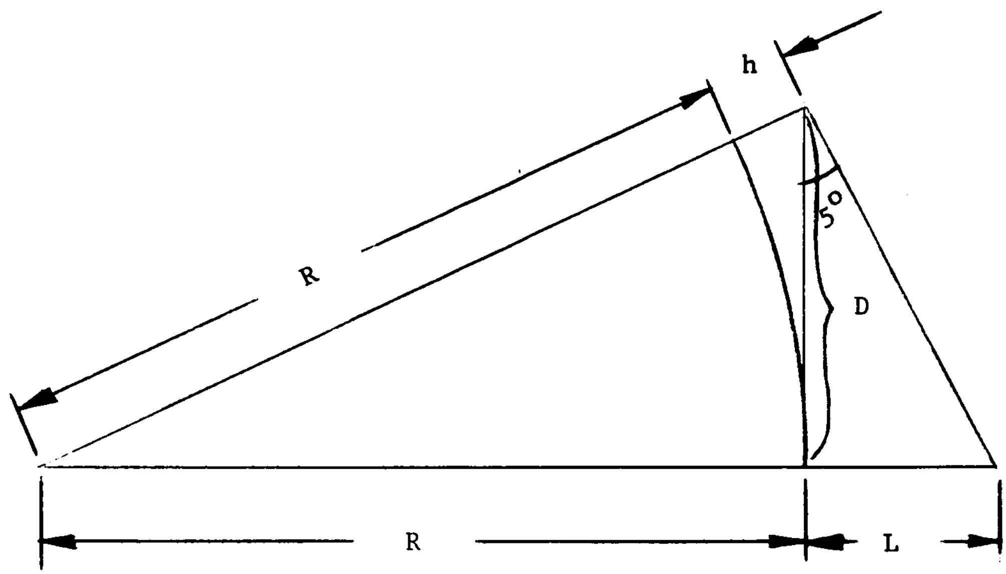


Figure 4. Geometric Relations Used to Determine Distance (D) to Lunar Horizon (Flat Surface) From 2-meter High Camera Eye View; and Height (L) at That Distance Which is Subtended by a 5° Vertical Field-of-View

Allowing 5 degrees FOV above the horizon line-of-sight, landmarks on the horizon of L relative altitude or less would be in full view, where

$$L = D \tan 5 \text{ degrees} - 465 \text{ meters}$$

To this 5 degrees FOV, 5 degrees will be added to allow for vertical scene jitter due to travel over very rough lurain, giving an upper bound for the vertical FOV as 10 degrees above the horizon line-of-sight. The total maximum VFOV has become 41 degrees, 10 degrees above the horizon line-of-sight and 31 degrees below.

A large FOV such as has been established here ($\cong$ 40 degrees vertical x 60 degrees horizontal) has the disadvantage of decreased resolution and increased chance of picture smear at velocities higher than the assumed 1 km/hr. Its advantages are minimal apparent picture jitter over rough lurain, opportunity to observe landmarks while moving, wider visibility for purposes of obstacle detection and avoidance, and decreased time required to obtain a panorama for navigation or science purposes when the vehicle is stopped.

Using a camera height of 2 meters above a flat surface and a D_{cw} = 0.5 meter (reference previous section), the D_s was found to be 7.89 meters (between front wheel surface contact and near edge of a hazardous crevasse). A 60 degree HFOV permits visibility to the left or right of a hazardous crevasse at this distance:

$$\tan 30 \text{ degrees} = \frac{x}{\sqrt{(2)^2 + (8.39)^2}}$$

x = 4.98 meters to the left or right of the hazardous crevasse.

This width is a comfortable margin for a vehicle $\leq$ 2 meters in width.

Traveling typically at 1/2 km/hr in hazardous terrain, the driver will have enough time to recognize a hazardous crevasse, assess both sides of the crevasse, and command the vehicle to follow the better evasive path. Thus, the outstanding guidance advantage of having a wide HFOV such as 60 degrees. The 40^o x 60^o FOV will be retained as the baseline design camera FOV for later development.

h) Minimization of Scene Jitter due, to Unstabilized Platform Mounting of TV Camera. Assume:

(1) 40 degrees vertical field-of-view.

(2) Limits of pitch and roll motion of the camera axis system at low vibration frequencies (< 4 cps) are ±10 degrees the vast majority of the time.

(3) Picture element = 0.1 degree x 0.1 degree.

Assumption (2) is made with the understanding that the vehicle bed has at least a torsion bar type suspension and perhaps a coulomb-type damping on the wheel frame. Therefore, ± 10 degrees angular motion after damping and vibration isolation represents considerably greater angular motion of the wheel moment arms about the vehicle c. g., i. e., a very rough lunar surface.

There are several factors that lend support to the idea that the pitch and roll motion of the camera axis system will be low frequency in nature and small in magnitude.

(1) The major portion of the lunar surface in the vicinities of all Surveyor and Apollo landing sites to date respond to the pressure of a mass as if it were like loose topsoil to a depth of approximately 4 to 6 inches. This is evident in the Surveyor footpad "footprints" and especially in the footprints of the astronauts. This "loose topsoil" response is significant in cushioning any uneven motion of the LRV, therefore reducing the magnitude of vehicle bed vibrations.

(2) Assuming the LRV wheels are large ($\cong$ 1 meter diameter) and resiliant in design, the wheels will be able to "straddle" the gap between small rocks, or a small rock and the surface, or the edges of a small crater, such that vibrations due to wheeling over these small perturbances will be significantly lower in frequency and smaller in magnitude than that obtained with normal sized or small wheels. The wheel resilience and relatively smaller mass compared to the vehicle body mass will permit the wheels to absorb the bulk of the high frequency perturbations.

For the assumed FOV, ± 10 degrees pitch motion represents a vertical shift of a flat horizon line of approximately ± 25 per cent of the total height of the scene. Roll motion of ± 10 degrees is relatively less disturbing, representing a rotation of ± 10 degrees about the center point of the scene.

It is evident that these unwanted changes can be nullified on the earth by processing pitch error and roll error telemetry to generate artificial scene shift or rotation equal in magnitude of the telemetry and opposite in phase. However, this method has two significant disadvantages:

(1) The pitch and roll errors for the camera axes coordinate system will be different in magnitude and phase than the pitch and roll errors for the vehicle body axes coordinate system. This is due to the long moment arm represented by the camera mast, which will cause a pendulous action (with the camera representing the mass at the end of an inverted pendulum) due to pitch and roll motion of the relatively heavier vehicle bed. The difference in magnitude and phase between the two sets of errors will, in general, be as unpredictable as the lurain causing the errors. The vehicle body axes pitch and

roll errors will be telemetered for navigational use. To telemeter the camera axes, pitch and roll errors would require pitch and roll error sensing devices mounted rigidly to the camera axes coordinate system, adding to the power and data processing requirements for the vehicle.

(2) The second disadvantage is that, even with appropriately accurate telemetry with which to "countershift" or "counter-rotate" the scene on the earth, a loss of information would occur.

If a picture were taken when the camera axes system pitched + 10 degrees, the artificially shifted scene on the earth would properly show the horizon line in the same location as if the + 10 degrees pitch had not occurred at all, but the bottom 10 degrees FOV would appear blank or black to account for the shift, and the bottom 10 degrees FOV may be the most important section of the TV scene much of the time for the purpose of obstacle detection.

The first disadvantage discussed may be minimized by appropriate vehicle design so that, with a sufficiently rigid camera mast, the phase and magnitude differences between the two sets of errors may approach constant values. In that event, the vehicle body axes system pitch and roll errors (appropriately biased) would be sufficiently accurate to use for scene jitter correction.

The second disadvantage is not as easily dismissed. However, there is a way by which it can be minimized — by time synchronization of the start of TV exposure time with the quiescent level crossing of the pitch error magnitude, where the quiescent level represents the time average pitch error. This appears like a simple solution to the problem. However, another problem comes into being; the zero crossing is invariably a point in the pitch error curve when the slope of the curve is large, and picture smear becomes very appreciable.

Without detailed assumptions and calculations, it will be assumed that the damped natural frequency of the LRV is $\cong$ 4 cps. Also, it is assumed that the wheels are large ($\cong$ 1 meter diameter), the camera exposure time is 10 ms, and the picture element size = 0.1 degree x 0.1 degree. Assume worst case conditions of transient vibrations (pitch) occurring between ± 10 degrees and at a 4 cps rate. The worst time for picture exposure occurs when the slope of the vibration curve is maximum, i.e., at times of zero crossing of the vibration curve, which occurs at $t = n/8$ seconds, where $n = 0, 1, 2, 3, \ldots$

The change in pitch angle over a 10 ms period centered at $t = 1/8$ second is:

$$\Delta W^{\circ} = 10^{\circ} \sin [2\pi\, 4\, (1/8 - 0.005)] - 10^{\circ} \sin [2\pi\, 4\, (1/8 + 0.005)]$$

$$= 10^{\circ} \sin [\pi\, (0.96)] - 10^{\circ} \sin [\pi\, (1.04)]$$

$$= 2.507 \text{ degrees.}$$

By contrast, the best time for picture exposure occurs when the slope of the vibration curve is minimum, i. e., at peaks of the vibration curve, which occur at $t = (n/8 - 1/16)$ seconds.

The changes in pitch angle over a 10 ms period centered at $t = (1/8 - 1/16)$ second is:

$$\Delta_B^\circ = 10^\circ\{\sin [\pi (0.46)]\}$$

$$= 0.0788 \text{ degree.}$$

Table 2 is a tabulation of vibration frequency (between ± 10 degree limits), the minimum and maximum pitch angle changes for any 10 ms period, and the corresponding percentage shift (picture smear) of a picture element. It is seen that even for a vibration frequency as low as 0.1 cps, there will be significant picture smear (62 per cent of a picture element size) in worst case. The best case (per cent shift-minimum) shows that at vibration frequencies as high as 1 to 2 cps the picture smear is tolerable (4.9 to 19.7 per cent). It is apparent that if the camera exposure period could be timed to be centered about a peak of a cycle of the vibration curve, the picture smear due to vibration would be minimized over that cycle.

This requirement is a counterposition from that requiring minimum scene jitter, as discussed earlier. However, minimization of picture smear due to vibration is apparently an overriding requirement compared to minimization of picture jitter due to vibration, as indicated by the extent of picture smear listed in the "per cent shift-maximum" column of Table 2.

Onboard circuitry as shown in Figure 5 would be a simple means of time synchronizing the start of the TV exposure period for minimum smear due to pitch error, yet also bound the picture jitter (to $\pm J^\circ$ in the comparison circuit). The astable multivibrator or an equivalent oscillator is presumed already onboard for the purpose of enabling the continuous TV mode while traveling. Therefore, the only additional circuitry is what <u>precedes</u> the astable multivibrator.

Figure 6 indicates that portion of interest of a sinusoid (or sum of damped sinusoids) when it is desired to start the TV exposure period so as to encounter minimum camera pitch angle change (E°) during the exposure. In general, t_s and t_E will not be symmetrical about t_{NULL} as the overall vibration characteristic (damped free vibration response to a surface perturbation by a complex degree-of-freedom system such as a four wheeled vehicle) will be the algebraic sum of a collection of damped sinusoid terms. If, however, it can be assured that $(t_{NULL} - t_s) \geq T_{EX}/2$, then it can be certain that $(t_E - t_s) \geq T_{EX}$, as $(t_E - t_{NULL})$ will in general be greater than $(t_{NULL} - t_s)$ for a damped sinusoid.

TABLE 2

SINE   15:29   FRI.   03/27/70

CPS	MIN DEG	(%) \ SHIFT-MIN	MAX DEG	(%) \ SHIFT-MAX
.1	4.93228 E-5	4.93228 E-2	6.28317 E-2	62.8317
.5	1.23368 E-3	1.23368	.314146	314.146
1	4.93443 E-3	4.93443	.628215	628.215
2	1.97328 E-2	19.7328	1.25581	1255.81
3	4.43804 E-2	44.3804	1.88217	1882.17
4	.078853	78.853	2.50666	2506.66
5	.123117	123.117	3.12869	3128.69
10	.489435	489.435	6.18034	6180.34
15	1.08993	1089.93	9.07981	9079.81
20	1.90983	1909.83	11.7557	11755.7

TIME: 1 SECS.

EDIT RESEQUENCE

READY.

```
LISTNH
100 LET P=0.1
110 LET A=3.14159265
120 LET H=0.005
130 PRINT "CPS","MIN DEG","\ SHIFT-MIN","MAX DEG","\ SHIFT-MAX"
140 DEF FNA(W)=10*(SIN((2*A*W)*((1/(2*W))-H)))
150 DEF FNB(X)=10*(ABS(SIN((2*A*X)*((1/(2*X))+H))))
160 DEF FNC(Y)=10*(SIN((2*A*Y)*((1/(4*Y))-H)))
170 DIM A(10)
180 FØR I=0 TØ 9
190 READ A(I)
200 LET C(I)=FNA(A(I))+FNB(A(I))
210 LET B(I)=10-(FNC(A(I)))
220 LET D(I)=100*((B(I))/P)
230 LET E(I)=100*((C(I))/P)
240 PRINT A(I),B(I),D(I),C(I),E(I)
250 NEXT I
260 DATA 0.1,0.5,1,2,3,4,5,10,15,20
270 END
```

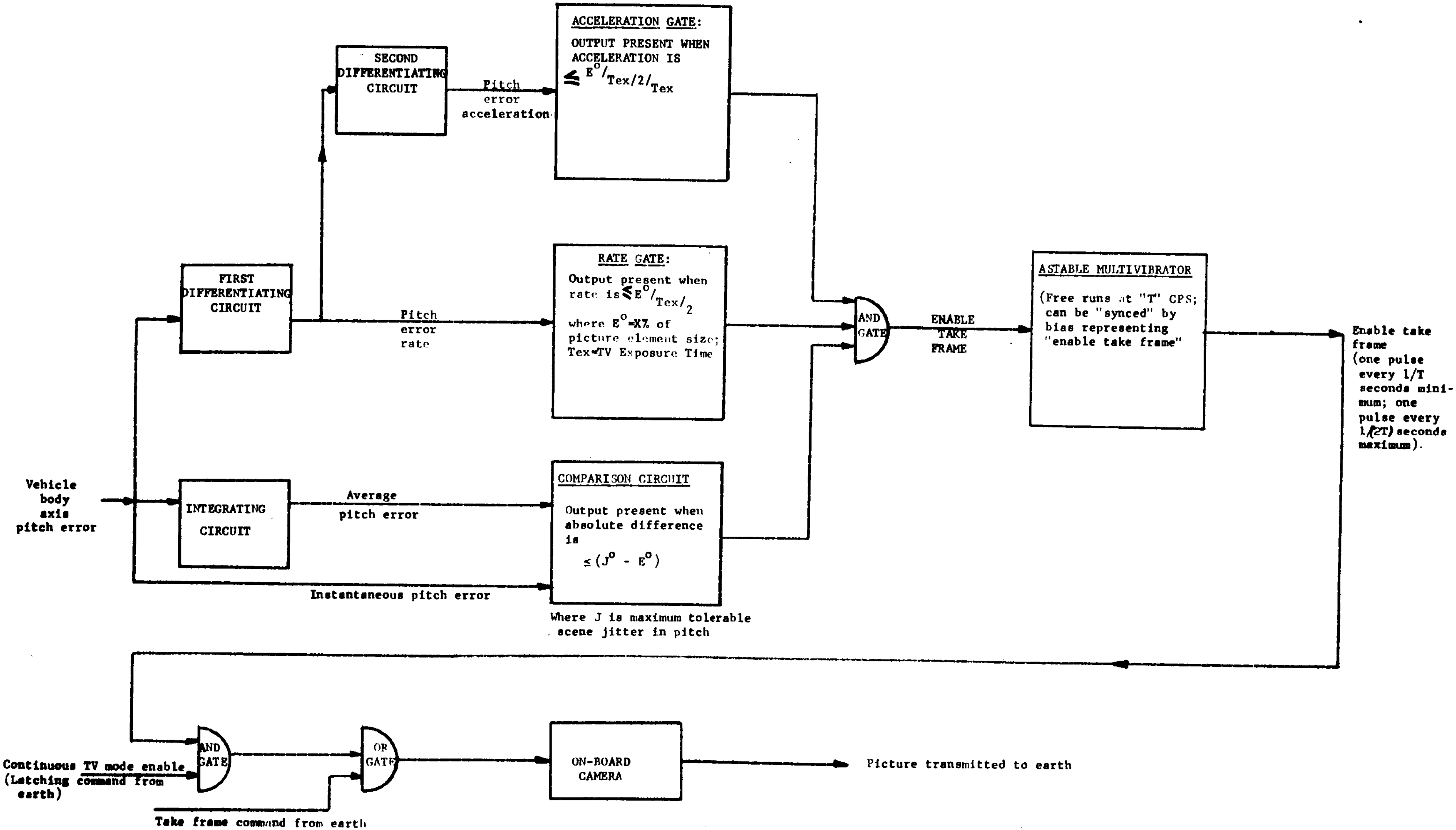


Figure 5. On-Board Circuitry Used to Minimize Scene Jitter and Smear

To recognize the point t_s, it is necessary to establish:

(1) The magnitude of the error is $\leq (J^\circ - E^\circ)$. This confines the picture jitter to the bounds of $\pm (J^\circ)$ and is accomplished by the comparison circuit of Figure 5.

(2) The magnitude of the error rate is $\leq E^\circ/(T_{EX}/2)$ for an exposure period straddling the portion of the vibration response shown in Figure 6, and is $\leq E^\circ/(T_{EX})$ for a nonstraddled portion.

Since a null point, i. e., zero error rate, in a damped sinusoid has lower values of error and error acceleration (and lower error rates at nearby points) than null points occurring previously in time, it is probable that the criteria for the earliest starting time for the exposure period would be met close in time to a null point but far enough away in time such that the exposure period would not straddle a null point. In such a probable event, the magnitude of the error rate at t_s must be set $\leq (E^\circ/T_{EX})$. (In truth, the upper bound on this rate can be set lower, but this is a design refinement that can be pursued at a later time.) This test is made by the differentiating circuit and subsequent rate gate of Figure 5.

(3) The magnitude of the error rate is decreasing, preferably at a deceleration which will ensure that the ensuing "time window," during which only E° change will occur, will be at least T_{EX} seconds long. The certain upper bound on this acceleration is $E^\circ/(T_{EX}/2)/(T_{EX})$ for an exposure period which straddles a null point and may be $E^\circ/(T_{EX})/(T_{EX}/2)$ for an exposure period which does not straddle a null point. (Conditions (1) and (2) could be met with faster acceleration, resulting in a "time window" $< T_{EX}$ seconds long.) Here, as in Condition (2), the upper bound can be set lower, but this is a design refinement that can be pursued later. This test is made by the second differentiating circuit and subsequent acceleration gate of Figure 5.

When all three conditions are met (AND gate of Figure 5), the astable multivibrator is triggered and, subsequently, the camera.

When all three conditions are not met, the astability of the multivibrator assures at least one frame every period of the multivibrator. Once the multivibrator is triggered, it cannot be retriggered until at least one-half of its cycle later. This assures a tolerable maximum frame rate. The frequency of the multivibrator could be made selectable at discrete levels to change the frame rate limits according to vehicle velocity.

Figure 7 illustrates the in phase relationship of roll error and pitch error due to the right front wheel rolling over a rock of height R. The only apparent way that only a roll error would occur while traveling over a

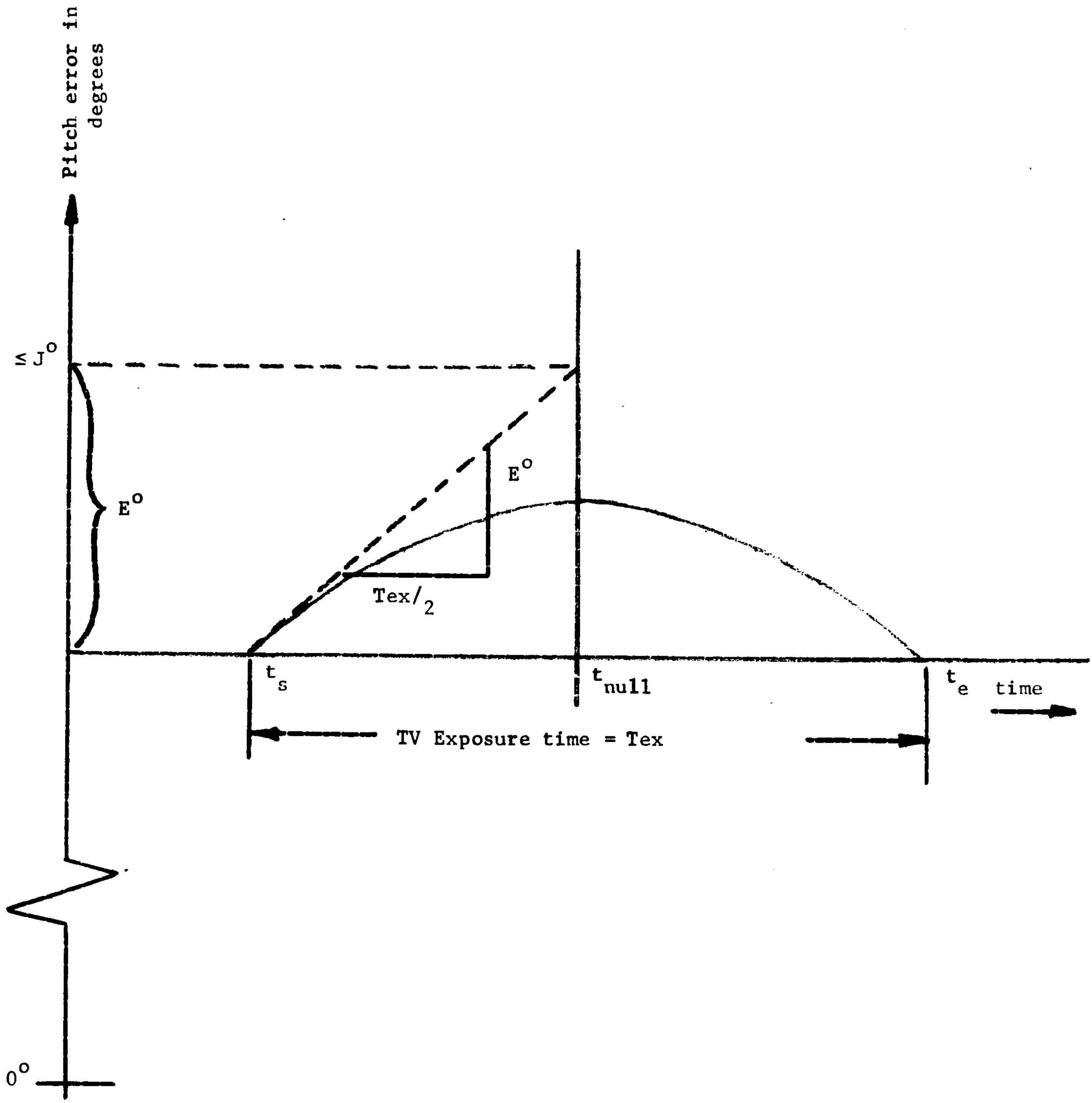


Figure 6. Segment of Sinusoidal Characteristic of Pitch Variation Due to Camera Vibration

rough surface would be if the right side wheels as a pair, or the left side wheels as a pair, began simultaneously rolling over prominences of the same height or crevasses of the same depth. Similarly, the only apparent way that only a pitch error would occur while traveling over a rough surface would be if the front wheels as a pair, or the rear wheels as a pair, began simultaneously rolling over prominences of the same height or crevasses of the same depth. Due to the random distribution of prominence sizes or crevasse sizes, the probability of generating a pitch error only or a roll error only is apparently low.

Because of the prominently in phase relationship of pitch and roll errors, it is reasonable to assume that their rates will be minimum simultaneously. Therefore, only one of the two errors has to be monitored to determine when minimum error rate occurs for both pitch and roll, as does the circuitry of Figure 5.

A point about an effect that should not be overlooked — translational motion of the vehicle c. g.:

Pure translational motion of the vehicle c. g. does not evidence itself in axes-rotation sensing devices which produce the pitch and roll error TM. Horizontal translational motion (in the direction of travel) has a significant effect on picture smear, as discussed earlier in this report. So, too, the vertical translational motion in Figure 7 (represented by Z_C) will contribute to the angular change, causing picture smear to the same degree that the horizontal translational motion did. A pure translational motion without any simultaneous axes rotation is at least as improbable (if not more so) as occurrence of roll error without pitch error or pitch error without roll error, due again to the randomness of prominence sizes and crater sizes.

Therefore, again, by monitoring only pitch error or roll error, it is reasonable to assume that minimum translational motion (Z_C) occurs at minimum pitch error. Therefore, the bounds $\pm J°$ in Figure 5 will also bound the absolute magnitude of Z_C contributing to picture smear.

3. Obstacle Detection Subsystem

The significant factors associated with an obstacle detection subsystem are: (a) reliability of detection and tradeoff between active and passive means of detection and (b) advantageous location on LRV.

a) Reliability of Detection and Active versus Passive Methods. Due to the ambiguities existing in attempting crevasse detection by TV alone, as previously discussed, a more reliable method is required. Crevasse detection would be least ambiguous, short of a tactile method, by use of a ranging method. Relying on a passive ranging method, be it ultraviolet, infrared, or any other band of the spectrum (however feasible or infeasible due to intensity level), would be basically no less ambiguous than a visual method, as the shadowing effects and indirect reflections would still exist but merely shifted in spectrum. An active ranging system would require a

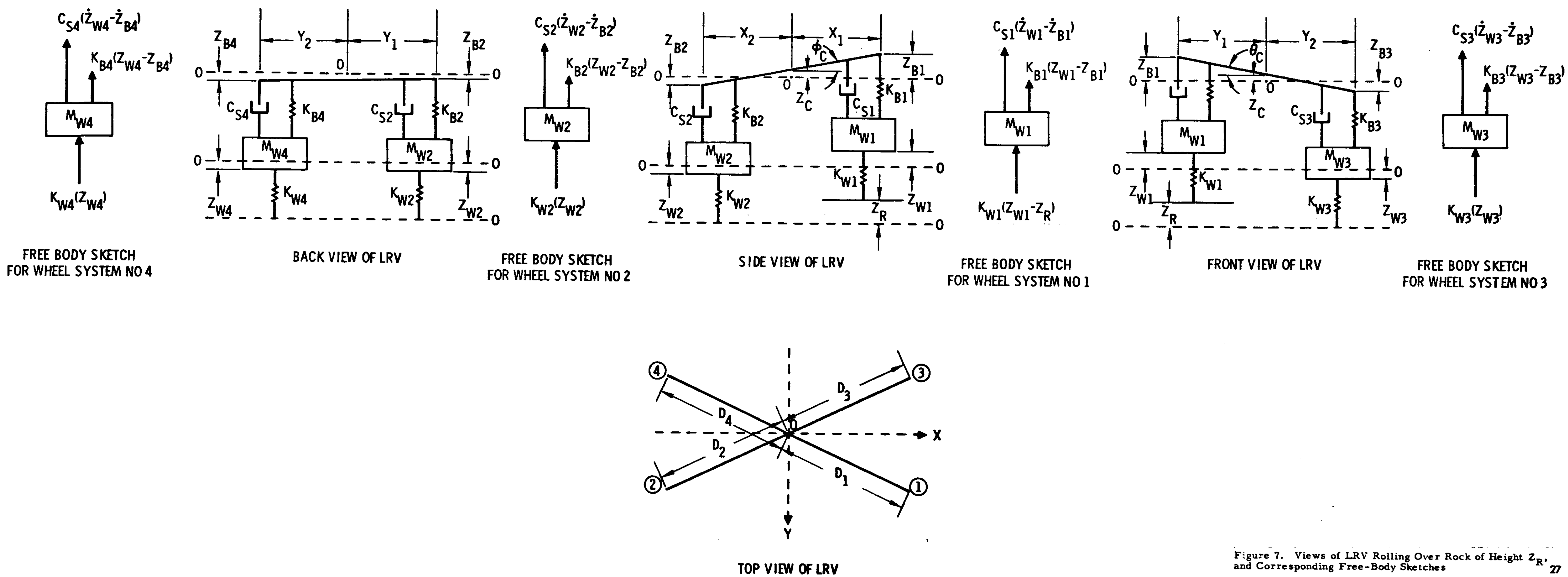


Figure 7. Views of LRV Rolling Over Rock of Height Z_R, and Corresponding Free-Body Sketches

very high frequency of operation to determine accurately the short distance ranging in question. Use of a tactile method such as a contact switch at the end of a lightweight boom supported at its end on a wheel system which tracks the surface it unreliable due to its questionable durability while attempting vehicle design maximum range traversal over rough lurain (Appendix A, Ref. 5)

b) Advantageous Location on LRV. A ranging system is best located high on the LRV for the same geometric considerations as discussed in the TV section (II. A. 2. f). An obviously desirable location would be at the same height as the TV, supported on the same mast, and directed sharply downward to the surface.

4. NAV/GUID Instrument Data.

Abrupt changes in vehicle attitude with respect to local vertical, in wheel motor current(s) and odometer(s), or exceeding thresholds for these parameters can be interpreted, via telemetry, as an impending obstacle encounter, e. g. , steep crater slope, or that an obstacle has been contacted. This is a tactile method, however, and warrants automatic onboard action to avoid the system time delay. No special instrumentation is needed for guidance beyond that required to fulfill navigation and vehicle housekeeping needs.

B. Obstacle Avoidance

The significant requirements here are: (1) expeditious stopping of the vehicle and (2) freedom of movement for circumvention of an obstacle.

1) Expedition Stopping. The obstacle detection subsystem and the NAV/GUID instrumentation previously discussed can be coupled easily to an onboard gating system which would generate an automatic stop when their appropriate hazard thresholds are exceeded. The information causing the automatic stop can be telemetered to earth for the purpose of ground backup.

2) Freedom of Movement. Apparent requirements beyond those required for nominal driving and velocity control are the capability to drive the vehicle in reverse, to turn a tight circle, and to have the option of high torquing at one or more wheels. The last item implies individual wheel drive. Additionally, variable velocity at low speeds would be desirable, but several discrete velocity levels should be sufficient.

C. Motion Control

1. General

Probability of a command link loss increases at high latitudes and longitudes, and especially in rough lurain. This bounds the lunar area available for remote controlled exploration.

Assume a velocity control loop closed on the earth, i. e. , dependent upon a steady stream of velocity commands. In the event of a sudden loss of command link from the earth, the vehicle would come to a halt after its momentum has dissipated. This does not represent a significant advantage for the closed loop on the earth technique, since, for example, a simple onboard velocity control gating system dependent upon the presence of received AGC above a certain threshold could do the same thing. However, it does point out the problem that the nonzero momentum present at the time of command link loss could carry the vehicle further into a region where commanding is not possible, and the mission would abort.

This problem must be circumvented by some onboard sensing system which, after an appropriate time delay (to insure that the command link loss was more than a momentary disruption), would reverse the previous direction of motion of the vehicle so as to retrace a path known reliable for commanding. It is a significant possibility that command link loss could occur as the vehicle is in the process of being driven down a steep crater wall toward the crater bottom. This would result in a greater distance traversed by the vehicle due to the nonzero momentum present at the time of command link loss. Further, simply reversing the direction of previous motion to retreat from the region may not be successful because:

a) Possible loose soil would prevent the vehicle from being driven backwards up the steep wall from a dead start on the wall.

b) The vehicle may have been in a turning mode or following a path other than a gradient line.

Straightforward reversal of previous motion direction without an onboard steering control (steering memory system) and in the presence of loose soil may not then result in a sufficiently accurate retrace of its track.

One approach for a solution to the above predicament may be to have the onboard capability so as to continue on the planned path to the crater bottom and up the opposite wall to the top of its rim. This requires onboard steering control and velocity control. This approach for a solution has the disadvantage, however, that any insurmountable obstacle encountered along this blind path may cause the vehicle to stop and abort the mission anyway. Satisfactory examination, if possible, for insurmountable obstacles would be required from the starting rim of the entire course across a crater from rim to rim, if this approach is adopted. This approach may be very attractive if the depression to be traversed is a rill, running many kilometers in length, instead of a crater or if the depression is bordered by insurmountable or very rough lurain and offers a less hazardous route.

2. Steering Control

Without specifying the nature of the heading reference, be it a directional gyro, sun compass, or some other device, it shall be assumed that it exists primarily for the purpose of navigation, is adequately accurate for that purpose, is capable of being updated if necessary, and that is provides a reliable error signal for heading changes from a preset heading reference.

The basic problem is how to maintain desired headings accurately and ON COURSE while the vehicle is in motion. The options are a closed loop onboard or closed loop on the ground, as shown in simplified diagrams in Figures 8 and 9.

It is assumed that there is no steering control parameter storage capability onboard for the system of Figure 9 and that a continuous stream of commands from the earth is necessary to keep the LRV pointed in the desired heading. (This, incidentally, has the apparent disadvantage of an added burden on the command link.) Perturbations caused by rough lurain and heading commands from the earth will produce in either system the same eventual result: a vehicle heading essentially identical to the commanded heading.

The fundamental advantage of the system in Figure 9 is shift of equipment complexity from the LRV to the ground. The difference in the timing from the system in Figure 8, however, will cause complications in staying on course. This is illustrated by an example in Figures 10, 11, and 12 of the responses by both systems to the same perturbations in heading caused by rough lurain.

Figures 10, 11, and 12 illustrate true heading, including changes in heading caused by perturbations such as steep prominences, small craters, or generally uneven lurain. Figure 12 demonstrates the advantage of onboard closed loop over closed loop on the earth. If the three perturbations cited in the example were multiplied, as they should be to account for real lurain, then keeping the vehicle on course will be a serious problem with the closed loop on the earth technique.

Granted, the error could be decreased by including velocity and time in the earth based correction system and "over correcting" to compensate for the time delay to a considerable degree, but the resultant system would still be significantly inaccurate compared to the onboard correction system.

The point here is that the system of Figure 9 not only results in greater errors for navigation via dead reckoning compared to that achievable with the system of Figure 8, but it becomes a "local," i. e., a guidance problem in the attempt to traverse an area (filled with hazards, for example) which requires accurate local maneuvering.

3. <u>Velocity Control</u>

a) Control Loop. The options here, as for steering control, include closed loop onboard versus closed loop on the earth. The two systems would be diagrammed similarly to Figures 8 and 9 regarding the locations of the one-way transmission time delays.

The differences in accuracy between the two systems would not be as dramatically large as the example illustrated by Figures 10, 11, and 12 but could be significant in an area of rough lurain where numerous heading changes and velocity changes are required in various combinations and where perturbations would add to the errors in dead reckoning. Closed loop on the earth would add another dimension to the remote driving control problem caused by the system time delay. Delayed velocity control could add significantly to the problem of steering control if each wheel were controlled individually in velocity. Such a system could quickly generate unwanted heading changes over rough lurain, in addition to the considerations of II. C. 2, as well as unwanted torsional strain on the LRV itself. Closed loop on the earth for velocity control increases the command traffic density.

b) Velocity and Torquing Levels. The factors to be considered here are velocity range and resolution of velocity levels within the range. There is no apparent advantage of driving at speeds much higher than 3 km/hr over unknown, predominately rough lurain in the face of the system time delay. The errors in steering control and obstacle detection would increase for higher velocities over what was indicated in examples previously discussed. Even apparently smooth lurain in a field-of-view could well be pockmarked with insurmountable crevasses, requiring 3 km/hr as a reasonable upper limit (refer to II. A. 2. f). It would be of extreme value to have a high torquing capability (and commensurately slow speed) to escape from having partly fallen into a crevasse or to negotiate a steep slope.

The resolution of velocity levels could be discrete, i. e., 2 or 3 fixed velocity levels, wherein it likely would be elected to use the lower levels of velocity for relatively rough lurain or to use a high torquing capability advantageously. It would be important to have a vernier control on each discrete level in the velocity control loop so as to be effective in maintaining a reasonable constant velocity level. This would simplify dead reckoning calculations and would be a necessity if odometric means of velocity measurement is not used.

4. Distance

The options here are planned start and stop capability on the earth only versus onboard and on the earth. An onboard planned start and stop capability requires a clock and gating system. There appears to be no guidance need for this capability nor any significant guidance advantage over a capability based on the earth only.

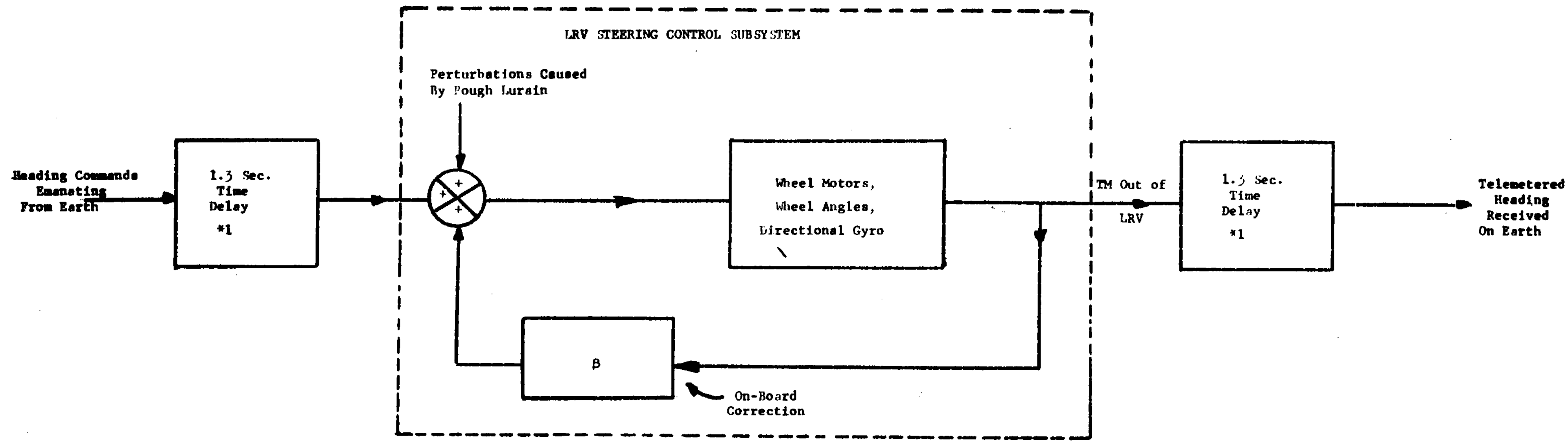
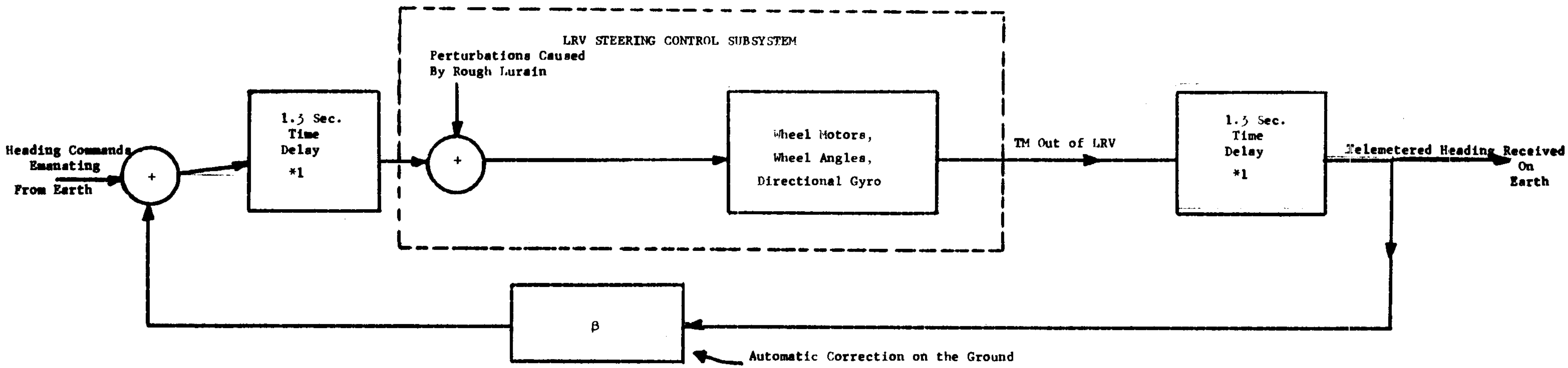


Figure 8. Steering Control Loop Closed On-Board



*1 = One-Way Moon-Earth Transmission Time.

Figure 9. Steering Control Loop Closed on the Earth

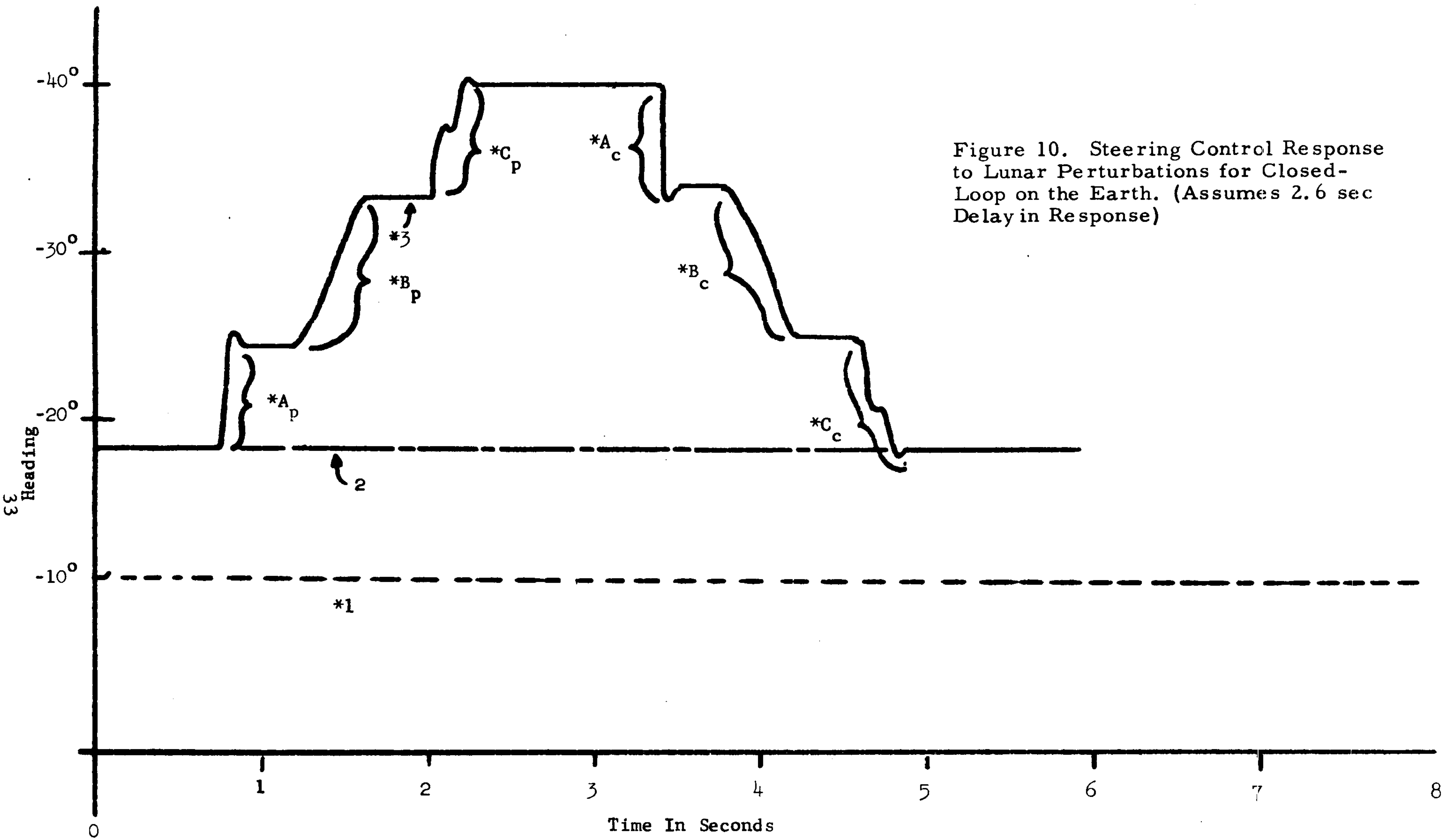


Figure 10. Steering Control Response to Lunar Perturbations for Closed-Loop on the Earth. (Assumes 2.6 sec Delay in Response)

*1	Arbitrarily established heading reference.
*2	Commanded heading, exclusive of automatic correction of perturbations caused by rough lurain.
*3	True heading as it appears in time at the LRV, as indicated by the on-board heading error-generating device.
*A_p, *B_p, *C_p	Changes in heading caused by perturbations.
*A_c, *B_c, *C_c	Time-delayed corrections of *A_p, *B_p, *C_p.

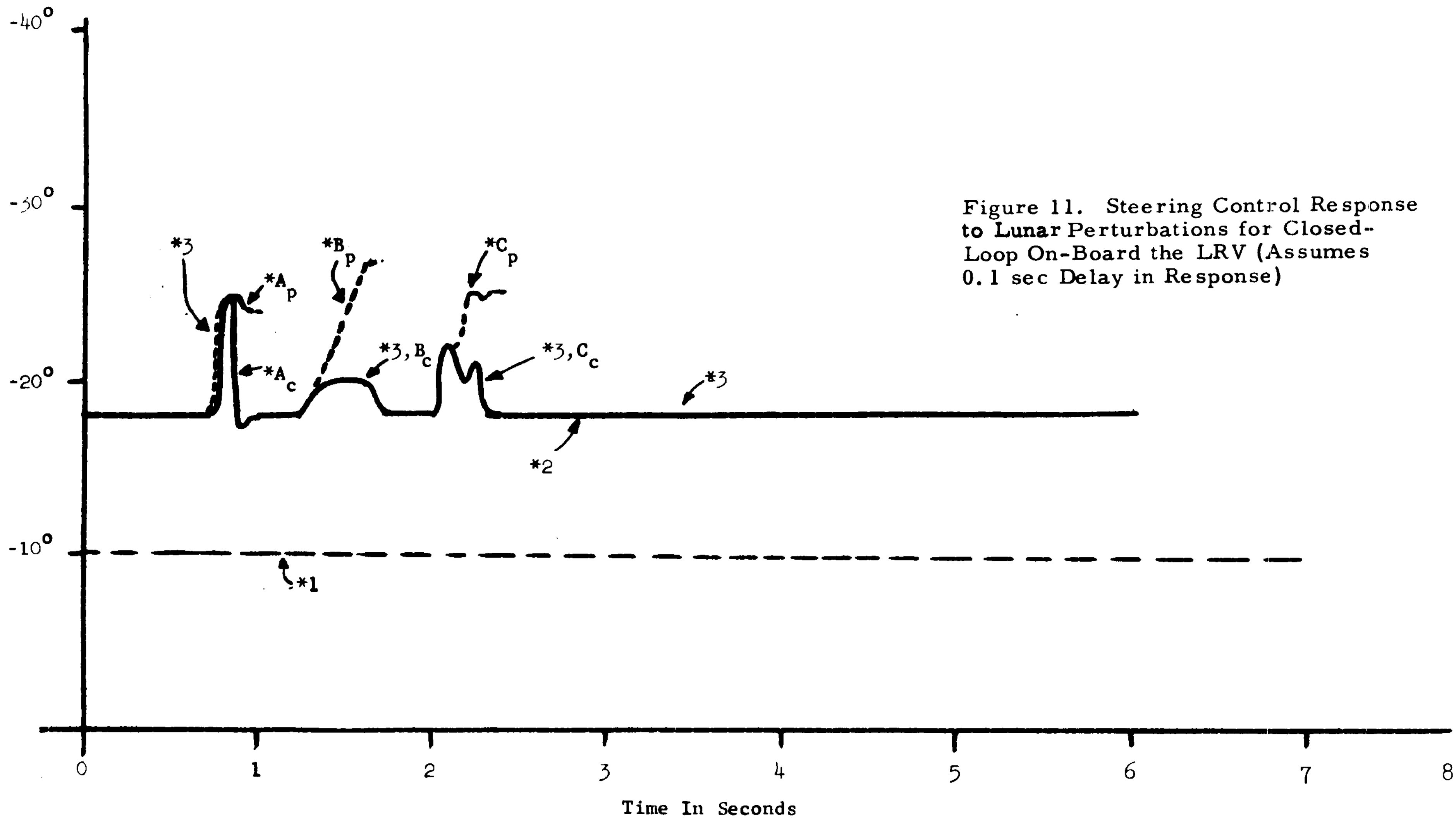


Figure 11. Steering Control Response to Lunar Perturbations for Closed-Loop On-Board the LRV (Assumes 0.1 sec Delay in Response)

***1, *2, *3, *A_p, *B_p, *C_p, *A_c, *B_c, *C_c - Same as notes for Figure 8 except time delay for *A_c, *B_c, & *C_c is assumed 0.1 second instead of 2.6 seconds as on Figure 8.**

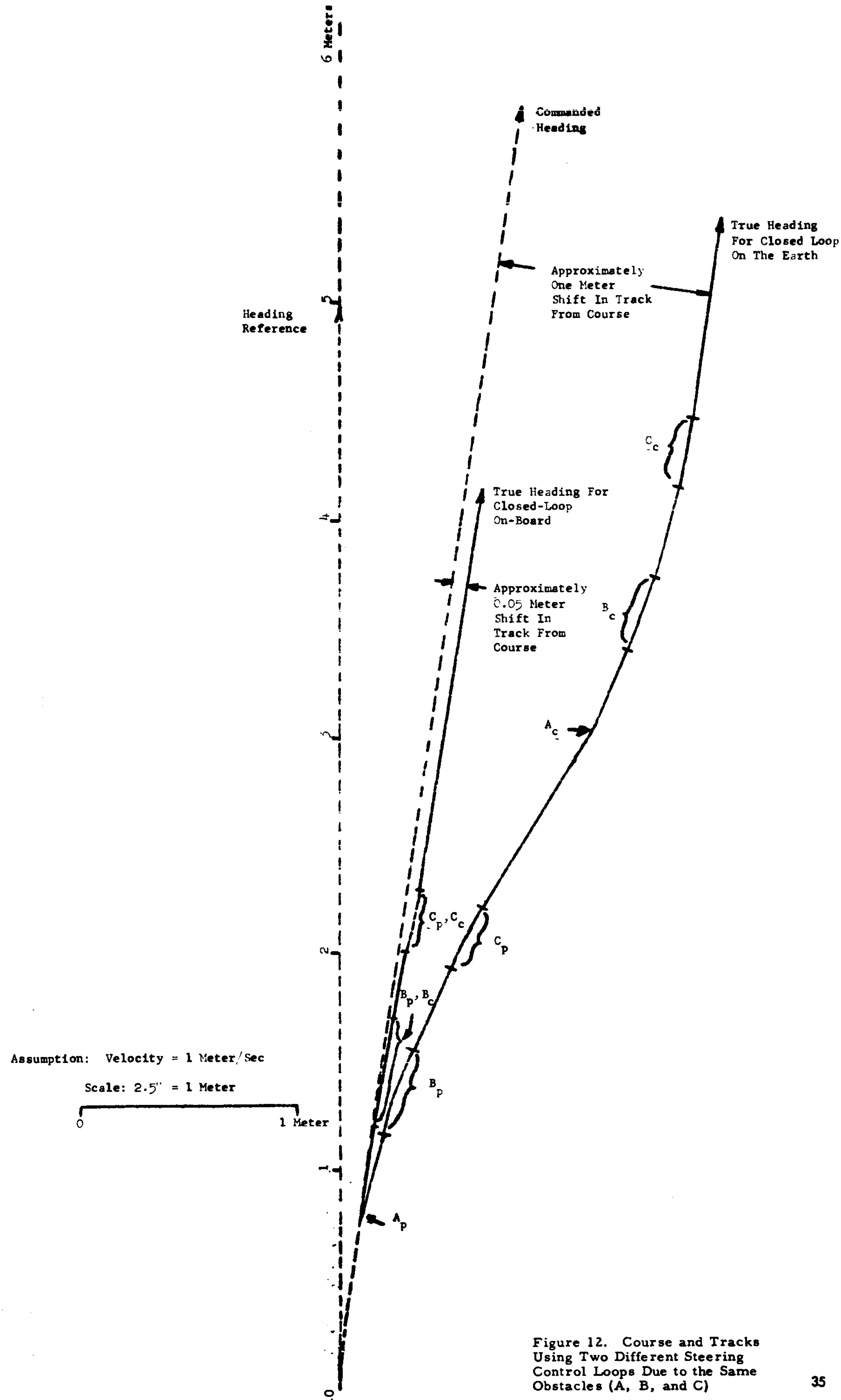


Figure 12. Course and Tracks Using Two Different Steering Control Loops Due to the Same Obstacles (A, B, and C)

III. Summary of Vehicle Baseline Design Applicable to Vehicle Remote Guidance

Based on the discussions of Section II, the following baseline design will be used for ensuing development of the Vehicle Remote Guidance portion of the MOC:

A. Obstacle Detection

1. TV

   a. 1 frame/sec to 4 frames/sec, depending on available information carrying capacity of the moon-earth information link. On-board circuitry as in II A. 2. h to minimize scene jitter and smear due to camera vibration.

   b. $0.1^\circ \times 0.1^\circ$ resolution

   c. 0.01 second exposure time

   d. Mounted on vertical mast on the forward part of the LRV and 2 meters above the lunar surface.

   e. Approximately $40^\circ \times 60^\circ$ FOV, with centerline of FOV directed 10° down from horizontal line of sight.

2. Obstacle Detection Subsystem (ODS)

Active, high frequency ranging device located near TV camera and directed sharply downward with primary purpose of crevasse detection.

3. NAV/GUID Instrument Package (NGIP), including some or all of accelerometers, inclinometers, motor current ammeters, directional gyro, and odometers.

B. Obstacle Avoidance

1. Automatic stop generated on-board when ODS or NGIP indicates transgression of a hazard threshold (including loss of command link).

2. Ground back-up computation of GO/NO-GO signals.

3. Remote-controlled steering control and velocity control to maneuver around obstacles.

C. <u>Motion Control</u>

1. Steering Control

   a. Automatic steering control maintains heading via on-board closed loop.

   b. Manual steering control overrides via ground control.. Automatic reversion to heading.

2. Velocity Control

   a. Automatic on-board closed-loop velocity control maintains one choice of discrete levels of velocity.

   b. Manual velocity overrides (selection of different choice of discrete velocity level) via ground control.

3. Distance

   Planned start and stop signals come from ground.

IV. TV DISPLAY AIDS FOR REMOTE DRIVING

A. Introduction

A description of Visual Aids (lines marking locations on a TV scene of predicted vehicle path, constant range lines from the predicted vehicle location, etc.) intended to be superimposed on a TV scene of the panorama in the direction of vehicle travel is presented herein. These visual aids would be accurately located on the TV scene as based on vehicle heading telemetry or commands, vehicle velocity telemetry or commands, and other pertinent telemetry or commands. While the single scene appears before the remote driver, these visual aids are capable of being updated in location each time a new sample of pertinent telemetry is received (or less often, if the TM rate is so high as to cause the visual aids to "jump" in the scene at a disturbingly high rate). At the appearance of the next TV frame (on the order of 1 second later), the visual aids would be automatically repositioned with respect to that new frame, and the process of "inter-picture" updating would begin anew. All the visual aids described ahead are designed to be optionally selected in nearly any combination.

A description and listing of the computer program used to transform these visual aids from the surface coordinate system to the TV image plane is included as well as a description of sample cases used to test the validity of the computer program, wherein travel through a simulated crater field is used as a backdrop and scenario.

Specific application of the above aids in generating a transparent overlay for use in driving the JPL vehicle is described and a survey of equipment commercially available which would interface with the computer program output is included.

It is assumed that the LRV camera takes a picture with the exposure time starting at (t_o) seconds; it is displayed in front of the remote driver at (t_o +6) seconds, and any speed change or heading change executed by the driver at (t_o +6) seconds will not be reacted upon by the LRV until (t_o +10) seconds.

It is also assumed that telemetry is in a usable form on the Earth 1.3 seconds after transmission from the moon.

IV. B. Description of the TV Display Aids

1. "Predicted Path"

a. Description. The "Predicted Path" (solid lines converging from the bottom of Figure 13 appearing on the TV scene at instantaneous time t_A [measured from (t_o +6 secs)] are the "paths" that the vehicle front wheel forward contact point (s):

1) a) have followed between ($t_o + t_a$) seconds and $[t_o + 6 + (t_A - 1.3)]$ seconds as indicated by odometric telemetry and heading telemetry;

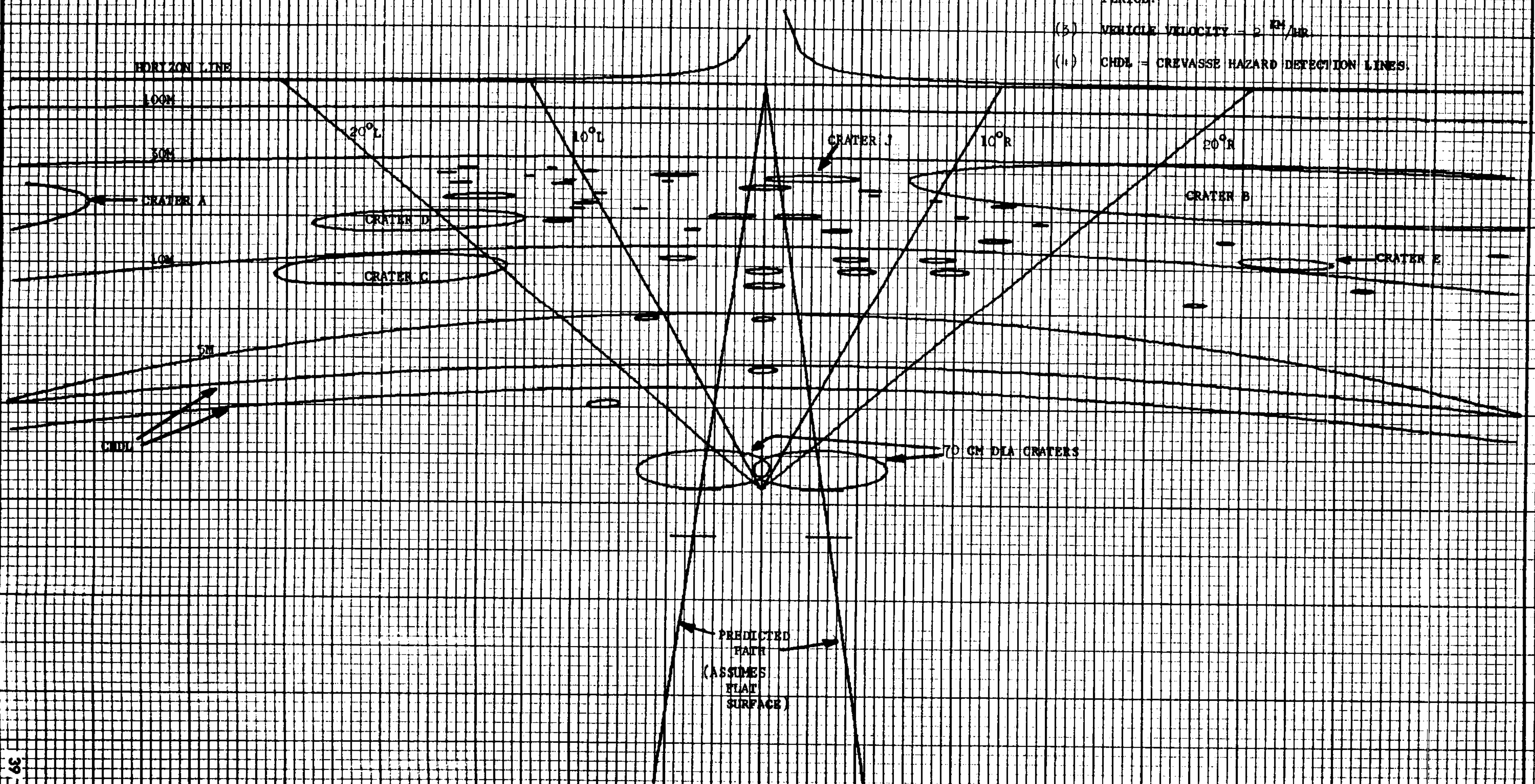
Figure 13.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH 0° HEADING (DUE EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) VEHICLE VELOCITY = 2 KM/HR.

(4) CHDL = CREVASSE HAZARD DETECTION LINES.



or: b) should have followed in the same time period as in (a) in response to speed change commands or heading change commands.

or: c) some combination of (a) and (b) where (b) is used to fill time periods of telemetry loss.

2) Will follow from $[t_o + 6 + (t_A - 1.3)]$ seconds to $[t_o + 10 + t_A]$ seconds as a result of

a) the heading in effect at $[t_o + 6 + (t_A - 1.3)]$ seconds.

b) commands issued from the earth between $[t_o + 2 + (t_A - 1.3)]$ seconds and $[t_o + 6 + t_A]$ seconds.

Note: This assumes a 4 second system response time.

3) Will follow from $(t_o + 10 + t_A)$ seconds and thereafter as a result of heading change commands executed on earth from $(t_o + 6 + t_A)$ seconds and thereafter.

IV. B. 1. b. Mathematical Representation in Surface Coordinate System

1) Single path from vehicle c. g:

a) From telemetry received between $(t_o + 1.3)$ seconds to $[t_o + 6 + (t_A - 1.3]$ seconds:

Consider the predicted path as composed of straight line segments, each segment the result of a vehicle heading change.

Assume heading changes occur at t_1, t_2, t_3, etc., at the vehicle.

(1) The first segment $[(t_o)$ to (t_1) seconds$]$:

$$X = 0 \text{ to } ①$$

$$Y = 0$$

$$Z = D_1$$

where

D_1 = distance between vehicle c. g. and its flat surface subpoint.

and ① = d_1, if TM link is OK.

① = $V_o (t_1 - t_o)$, if TM link is lost.

where d_1 = distance traveled between t_o and t_1, as indicated by telemetry received between $(t_o + 1.3)$ and $(t_1 + 1.3)$.

v_o = most recent velocity commanded, as of (to -4).

(2) The second segment is:

$$\begin{cases} \tan(\alpha_1 - \alpha_o) = \dfrac{X-X_1}{Y-Y_1} \\ Z = D_1 \end{cases} \quad \text{or:} \quad \begin{aligned} X &= (Y - Y_1)\left(\tan(\alpha_1 - \alpha_o)\right) + X_1 \\ Y &= Y_1 \text{ to } ② \\ Z &= D_1 \end{aligned}$$

where α_b = true heading from telemetry received at $(t_b + 1.3)$, if TM link is OK, (where $b = 0, 1$).

α_b = most recent commanded heading as of $(t_B - 4)$ if TM link is lost (where $b = 0, 1$).

② = $d_2 \sin(\alpha_1 - \alpha_o)$, if TM link is OK.

② = $v_1 (t_2 - t_1) \sin(\alpha_1 - \alpha_o)$, if TM link is lost.

where

d_2 = distance traveled between t_1 and t_2 as indicated telemetry received between $(t_1 + 1.3)$ and $(t_2 + 1.3)$.

v_1 = most recent velocity commanded, as of $(t_1 - 4)$.

X_1 = value of X at end of first segment

Y_1 = value of Y at end of first segment (= 0)

(3) The n^{TH} segment is:

$$\tan(\alpha_{n-1} - \alpha_o) = \frac{X - X_{n-1}}{Y - Y_{n-1}} \quad \text{or} \quad X = (Y - Y_{n-1}) \tan(\alpha_2 - \alpha_o) + X_{n-1}$$

$$Y = Y_{n-1} + (n)$$

$$Z = D_1$$

where

α_c = true heading from telemetry received at $(t_c + 1.3)$, $c = n-1, 0$, if TM link is OK.

α_c = most recent commanded heading, as of $(t_c - 4)$, if TM link is lost, or if TM for this time bracket has not yet been received.

(n) = $d_n \sin(\alpha_n - \alpha_o)$, if TM link is OK.

(n) = $v_{n-1}(t_n - t_{n-1}) \sin(\alpha_{n-1} - \alpha_o)$ if TM link is lost, or if TM for this time bracket has not yet been received.

d_n = distance traveled between t_{n-1} and t_n, as indicated telemetry received between $(t_{n-1} + 1.3)$ and $(t_n + 1.3)$.

v_{n-1} = most recent velocity commanded as of $(t_{n-1} - 4.)$

x_{n-1} = value of X at end of $(n-1)^{th}$ segment

y_{n-1} = value of Y at end of $(n-1)^{th}$ segment

IV. B. 1. b. 2 Two Line Path Extending from Two Front Wheels

Same as in IV. B. 1. b. 1.

X with $(X + D_3)$

Y with $(Y - D_2/2)$ and $(Y + D_2/2)$.

Results are two sets of equations representing right front wheel track and left front wheel track.

Where D_2 = distance between two front wheels (between midpoints of the wheel widths).

D_3 = distance along X axis between vehicle c. g. flat surface subpoint and front wheel flat surface contact point.

Note: Assuming the next picture is at (t_o + 1) seconds (when the camera responds to "take picture" commands), then the equations of IV. B. 1. b will apply with each time used in the equations increased by 1 second (effectively, a translation along the X axis). When the picture is taken at, or after $t = t_1$ (the first occurrence of a heading or speed change from t_o), then each time in the equations is increased by t_1 seconds (translation), and transformation about Z axis occurs: (Z X formation).

$$\begin{pmatrix} X_{\geq t_1} \\ X_{\geq t_1} \\ Z_{\geq t_1} \end{pmatrix} = \begin{pmatrix} \cos(\alpha_1 - \alpha_o) & \sin(\alpha_1 - \alpha_o) & 0 \\ -\sin(\alpha_1 - \alpha_o) & \cos(\alpha_1 - \alpha_o) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_{< t_1} \\ Y_{< t_1} \\ Z_{< t_1} \end{pmatrix}$$

Similar transformations occur whenever a picture reflects a heading different from the heading of the previous picture. The transformation angle will be the algebraic difference in headings between the two pictures taken in sequence. Translations always occur between pictures, reflected in the equations of IV. B1. b with the addition of the time between pictures to all times stated in the equations.

IV. B. 2 Possible Path

a. Description

The "possible path" (converging lines in Figure 13) are straight line extrapolations from the end of the "predicted path" of the path the front wheel surface contact points will follow along the heading determined by the actual joystick position at (t_o + 6 + t_A) seconds, allowing for the 4 seconds system reaction time. This "possible path" is assumed unexecuted until the driver pushes an execute button, as in the Bendix scheme.

The "possible path" appears on the "t_o" picture (i. e., picture exposed at t_o sec) starting at the end points ($t_o + 10 + t_A$ sec) of the predicted path. As time progresses, the predicted path ending points (and possible path starting points) converge into the distance.

b. Mathematical Representation in Surface Coordinate System

1. Single path from c. g.:

This path can be represented as the $(n + 1)^{th}$ segment, with the equations and term definitions of IV. B. 1. b. 1. (a) (3) applying with the substitution $n = n + 1$.

2. Two line path:

Same as IV. B. 1. b. 2, but applying to the equations of IV. B. 2. b. 1 above.

Note: The note of IV. B. 1. b. 2 applies to the above equations.

IV. B. 3. Projected Vehicle Image (at t > or = + 10 sec).

a. General

Let $X_{t_{N+1}}$, $Y_{t_{N+1}}$, $Z_{t_{N+1}}$ represent the coordinates for vehicle c. g. at $(t_o + 10 + t_a)$ sec for a picture exposed at t_o sec.

Assume, D_4 = wheel width

D_5 = distance between centers of left front and left rear wheels (same for right pair).

D_1, D_2, D_3 as defined previously.

b. <u>Mathematical Representation in Surface Coordinate System</u>

1. Coordinates of points on 4 wheel contact lines:

$$
\underbrace{\begin{bmatrix}
X = X_{t_{N+1}} + D_3 \\[2ex]
Y = \left[-\left(\dfrac{D_2}{2} + \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \text{to} \left[-\left(\dfrac{D_2}{2} - \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \\[2ex]
Z = 0 + Z_{t_{N+1}}
\end{bmatrix}}_{\text{Left Front Wheel}}
\begin{matrix} = \\[2ex] = \\[2ex] = \end{matrix}
\underbrace{\begin{bmatrix}
X_{t_{N+1}} + D_3 \\[2ex]
\left[+\left(\dfrac{D_2}{2} + \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \text{to} \left[+\left(\dfrac{D_2}{2} - \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \\[2ex]
0 + Z_{t_{N+1}}
\end{bmatrix}}_{\text{Right Front Wheel}}
$$

$$
\underbrace{\begin{bmatrix}
X = X_{t_{N+1}} + D_3 - D_5 \\[2ex]
Y = \left[-\left(\dfrac{D_2}{2} + \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \text{to} \left[-\left(\dfrac{D_2}{2} - \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \\[2ex]
Z = 0 + Z_{t_{N+1}}
\end{bmatrix}}_{\text{Left Front Wheel}}
\begin{matrix} = \\[2ex] = \\[2ex] = \end{matrix}
\underbrace{\begin{bmatrix}
X_{t_{N+1}} + D_3 - D_5 \\[2ex]
\left[-\left(\dfrac{D_2}{2} + \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \text{to} \left[-\left(\dfrac{D_2}{2} - \dfrac{D_4}{2}\right) + Y_{t_{N+1}}\right] \\[2ex]
0 + Z_{t_{N+1}}
\end{bmatrix}}_{\text{Right Front Wheel}}
$$

2. Outline of vehicle front:

Assuming front of vehicle bed is a distance D_7 along X axis from vehicle c. g. :

<u>Front of Vehicle Bed</u>

$$X = D_{t_{N+1}} + D_7$$

$$Y = \left[-\left(\frac{D_2}{2} - \frac{D_4}{2}\right) + Y_{t_{N+1}}\right] \text{to} \left[+\left(\frac{D_2}{2} - \frac{D_2}{2}\right) + Y_{t_{N+1}}\right]$$

$$Z = -D_{12} + Z_{t_{N+1}}$$

where

D_{12} is height of vehicle front above flat surface.

Assuming wheels are D_6 in diameter:

Forward Points of Front Wheels

$$\underbrace{\begin{bmatrix} X = X_{t_{N+1}} + D_3 + \frac{D_6}{2} \\ Y = \left[-\left(\frac{D_2}{2}+\frac{D_4}{2}\right)+ Y_{t_{N+1}}\right] \text{to} \left[-\left(\frac{D_2}{2}-\frac{D_4}{2}\right)+ Y_{t_{N+1}}\right] \\ Z = -\frac{D_6}{2} + Z_{t_{N+1}} \end{bmatrix}}_{\text{Left Front Wheel}} = \underbrace{\begin{bmatrix} X_{t_{N+1}} + D_3 + \frac{D_6}{2} \\ \left[+\left(\frac{D_2}{2}+\frac{D_4}{2}\right)+ Y_{t_{N+1}}\right] \text{to} \left[+\left(\frac{D_2}{2}-\frac{D_4}{2}\right)+ Y_{t_{N+1}}\right] \\ -\frac{D_6}{2} + Z_{t_{N+1}} \end{bmatrix}}_{\text{Right Front Wheel}}$$

IV. B. 4. Grid System

a. Description

Constant range and constant heading angle lines focused on the $(t_o + 10 + t_a)$ sec. point.

b. Mathematic Representation in Surface Coordinate System

In general:

1. Constant heading (radial) lines:

$X_s = X_{t_{N+1}}$ to N (large number at $\Delta = 0.1$ intervals)

$Y_s = (X_s \tan \beta) + Y_{t_{N+1}}$

where

$\beta = n\,10^\circ$

$n = 0, \pm 1, \pm 2$

$Z_s = 0$

2. Constant range lines (concentric circles):

$$(|X_s| - X_{t_{N+1}})^2 + (Y_s - Y_{t_{N+1}})^2 = R^2, \quad Z_s = 0$$

$R = R(1)$ through $R(5)$ = any 5 range values.

IV. B. 5 Crevasse Hazard Recognition Aid

Two semicircular arcs centered on camera axes origin lunar surface subpoint.

$$(X_s - D_8)^2 + Y_s^2 = R^2 \qquad X = 0$$

where
$$R = \begin{cases} K \\ K + C_H \end{cases}$$

C_H = width of hazardous crevasse

D_8 = X distance between vehicle c. g. surface subpoint and camera focal point surface subpoint.

This is based on the fact that an assumed minimum angle of 1 degree required for proper recognition is the angle that subtends a crater C_H in diameter at a surface distance of K from the surface subpoint of a camera axis origin located D above the surface.

IV. C Description of the Computer Program Interfacing Between Vehicle Telemetry and TV Display

1. General - The computer program, written in FORTRAN IV language, contains the appropriate transformation equations used to transform the visual aids specified in the surface coordinate system as chains of points into the TV image plane. The process is described diagrammatically in Figure 14.

2. Input Requirements - The required inputs to the program include:

a) Vehicle dimensions (Ref. Figure 34 of IV. E)

D_1 = distance between vehicle c. g. and its flat surface subpoint

D_2 = distance between two front wheels (between midpoints of the wheel widths)

D_3 = distance along X axis between vehicle c. g. flat surface subpoint and front wheel flat surface contact point

D_4 = wheel width

D_5 = distance between centers of left front and left rear wheels (same for right pair)

D_6 = wheel diameter

D_7 = distance along X axis between vehicle c. g. flat surface subpoint and front of vehicle bed

D_8 = ΔX (in translation BC) = X distance between vehicle c. g. surface subpoint and camera rotation system origin subpoint

D_9 = ΔY (in translation BC) = Y distance between vehicle c. g. surface subpoint and camera rotation system origin subpoint

D_{10} = ΔZ (in translation BC) = vertical distance between vehicle c. g. and camera rotation system origin

D_{11} = distance between camera axes focal point and image plane

IV. C. 2. b) <u>General Parameters:</u>

PDLY = Delay in seconds between the time the camera exposure period began and the instant when the picture is first displayed in front of the remote driver.

TMDLY = Delay in seconds between the time the LRV first senses a telemetered parameter (voltage, current, temperature, vehicle body orientation, vehicle speed, etc.) and the telemetered parameter is stored in memory (and thereafter accessible by the computer program).

CMDLY = Delay in seconds between the time a command that has been sent to the LRV is stored in memory (and thereafter accessible by the program) and the instant the LRV begins to respond to the command.

HFOV, VFOV = Horizontal and vertical field of view in degrees.

CS = Minimum size (width in direction of travel) of a hazardous crevasse

RA = Minimum vertical field of view in degrees which subtends a crevasse of hazardous size when such a crevasse first becomes recognizable as harzardous (disregarding shadowing effects).

JSH = Instantaneous joystick heading.

RVPICS = Vertical height (linear) of the picture displayed in front of the remote driver.

TMR = Prevailing telemetry rate in samples per second.

c) Telemetry Requirements (stored in memory from (t_o + TMDLY) seconds and thereafter where t_o = time exposure period began):

1) Camera elevation with respect to plane of vehicle frame.

2) Camera azimuth with respect to plane of vehicle frame.

3) True vehicle heading (this may also have been calculated based on other TM).

4) Vehicle velocity (this may also have been calculated based on other TM).

5) Vehicle pitch. (This may also have been calculated based on other TM.)

6) Vehicle roll. (This may also have been calculated based on other TM.)

7) TM parity check for the above.

d) Command Requirements (stored in memory from (t_o - CMDLY) seconds and thereafter):

Same as 1) through 4) of paragraph c) above.

3. <u>Program Listing</u>

a) Total listing, including simulation cards for test cases: Appendix D contains a complete listing of the program in FORTRAN IV language, including all cards required for TM simulation and crater field simulation for use in the case tests of the program (see IV. D. ahead for description of the sample cases).

IV. C. 3. b <u>Operational Listing</u>

The operational listing is contained in Appendix E. This listing operates in 0.265 seconds per TV frame.

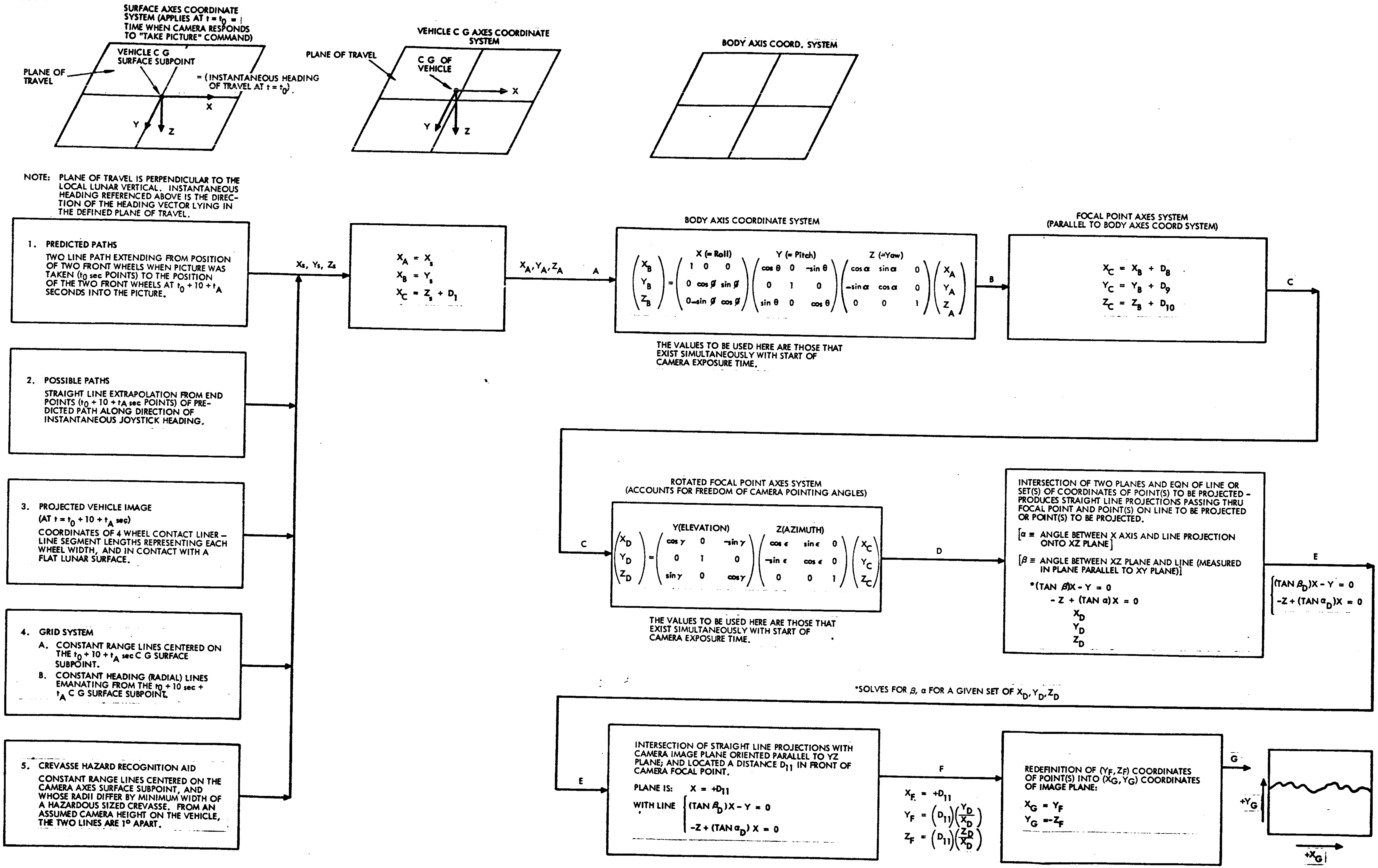


Figure 14. Translations and Transformations From Surface Coordinate System to Camera Image Plane – Used in Remote Driving Aids Computer Program

IV. D Sample Case Used to Test the Visual Display Aids Computer Program

1. General

The total listing of Appendix D was used for the sample case to generate the t = 87 seconds through t = 104 seconds pictures (Figures 19 through 29).

A minor variation of the total listing was used to generate the t = 0 second pictures (Figures 1, 16, 17, 18, 30, 31, 32, 33).

2. Sample Case - Traversal in a Typical Crater Field

Assume a typical crater field as in Figure 15. Assume that a full panorama had been taken at the t = 0 second point (Figures 16, 17, and 18), while the vehicle was stationary, in preparation for traversal to the east in the crater field.

At the t = 0 second point, craters A through G subtend vertical FOV angles in the partial TV panorama of the crater field as shown in Table 3.

Using the criterion that a crevasse must subtend a vertical FOV angle of $\geq 1^{o}$ ($\cong$ 12 lines of a 500-line scan, Ref. BSR-2815, January 1970) to be properly recognized (ignoring shadowing effects for the moment), it is seen from Table 3 that only craters A, B, and C are "recognizable" from the t = 0 second viewing point. (NOTE: On a 10 meter resolution map of the lurain, only craters A and B would be recognizable and would appear on this map as not much larger than two "dots.")

Making the decision to proceed east (realizing that the traversal will be between craters B and C), the remote driver commands a velocity of 1/8 meter per second ($\cong$ 1/2 KM/hr.). He turns on the CREVASSE HAZARD RECOGNITION display aid to determine if a crevasse is hazardous ($\geq$ 0.7 meters diameter) or not, as soon as it is properly recognizable on the screen. (NOTE: A 0.7 meter diameter crevasse subtends a vertical FOV of 1^{o} as seen by the camera at a surface distance of 8.73 meters to the center of the crevasse from the subpoint of a camera located 2 meters above the surface. Therefore, the CREVASSE HAZARD RECOGNITION display aid consists of two lines at constant ranges of (8.73 -0.35) meters and (8.73 + 0.35) meters from the lunar surface subpoint of the camera axes system origin at the time the picture was taken. If a crevasse fills the space between these two range lines, it is recognized as hazardous.)

From the picture taken at t = 88 seconds (Figure 20), the remote driver just begins to recognize craters F and G as being hazardous in size (see Table 4). He immediately switches to the GRID display aid (Figure 21) to aid in determining the required heading angle change to circumnavigate these craters starting at the predicted ($t_{EXP.}$ + 10 seconds) vehicle position.

TABLE 3. SUBTENDING ANGLES FOR CRATERS AS VIEWED FROM t = 0 SECOND LOCATION

CRATER IDENTIFICATION	CRATER DIAMETER (=D)(METERS)	DISTANCE (=R) TO FAR EDGE OF CRATER FROM t = 0 SECOND POINT (METERS)	VERTICAL FOV ANGLE (α) SUBTENDED BY CRATER FROM t = 0 SECOND POINT $\left[\tan \alpha = \frac{2D}{4 + R(R-D)}\right]$ (ASSUMES CAMERA IS MOUNTED 2 METERS ABOVE LUNAR SURFACE) (CALCULATED & LISTED IN TABLE 4)
A	2.0	36.3	3.8°
B	1.6	37.0	2.3°
C	2.4	15.7	1.3°
D	3.0	21.1	0.9°
E	1.0	16.5	0.44°
F	0.7	20.35	0.202°
G	0.7	20.35	0.202°
H	1.2	24.3	0.24°
I	1.0	26.0	0.18°
J	2.0	29.0	0.29°
K	1.0	29.7	0.13°

TABLE 4. CRATER COMPUTER PROGRAM LISTING AND OUTPUT

```
CRATER     18:00     TUES.  06/02/70
   100 C=180/3.14159265
   110 DIM D(21), Y(21),A(21)
   120 FOR I=0 TO 10
   130 READ D(I)
   140 NEXT I
   150 RESTORE
   160 FOR I=11 TO 21
   170 READ D(I)
   180 NEXT I
   190 FOR K=0 TO 21
   200 READ Y(K)
   210 A(K) =(2*(D(K)))/(4+((Y(K))*((Y(K))-(D(K)))))
   220 PRINT"      =";(C*ATN(A(K)))
   230 NEXT K
   240 DATA 20,16,2.4,3.0,1.0,0.7,0.7,1.2,1.0,2.0,1.0
   250 DATA 36.3,37,15.7,21.1,16.5,20.35,20.35,24.3,26.0,29.0,29.7,
   260 DATA 20.6,26.3,5.6,9.8,7.0,9.4,9.4,12.6,13.8,16.8,17.5

   RUN

CRATER     18:01     TUES.  06/02/70
   A  =  3.84159
   B  =  2.34628
   C  =  1.29211
   D  =  .890743
   E  =  .44115
   F  =  .19861
   G  =  .19861
   H  =  .243236
   I  =  .175216
   J  =  .291207
   K  =  .133808
   A  =  67.7554
   B  =  6.63993
   C  =  12.3516
   D  =  4.85492
   E  =  2.48955
   F  =  .93503
   G  =  .93503
   H  =  .931303
   I  =  .634336
   J  =  .907076
   K  =  .391423

TIME:     2 SECS.
```

These are angles in degrees subtended by craters viewed from vehicle location at t = 0 second (first group, A–K)

These are angles in degrees subtended by craters viewed from vehicle location at t = 88 seconds (second group, A–K)

Using the POSSIBLE PATH between craters D and F (Figure 21), he notes that travel along this course would require traversal directly across some small craters without much margin for maneuvering due to the locations of craters D and F.

He switches the POSSIBLE PATH to the south of crater G (Figure 22). There is a smoother path and safer margin for travel along this route than the previously considered POSSIBLE PATH. He concludes this because:

- Earlier frames evidenced no hazardous craters between craters G and E.

- Although crater B looms directly ahead along this route, he anticipates enough margin for a north-easterly course once he has passed a point along a line between craters E and G.

Therefore, he elects to take a southeasterly bypass route (heading = + 28° south of due east), commanding this heading change at t = 96 seconds (it takes effect on the moon an assumed 4 seconds later) (Figures 28 and 29).

Figures 30, 31, 1, 32 and 33, which show the crater field from the t = 0 second point, also include the projected vehicle image location for 1/2, 1, 2, 3, and 4 KM/hour velocities, respectively. (Figures 30 and 31 were taken with the camera azimuth angle at -40° and -20° respectively, instead of the nominal -10°, in order to ensure that the projected vehicle image was included in the vertical field-of-view. The -40° camera azimuth angle, used in Figure 30, causes the crater field to be excluded entirely.)

Figures 30, 31, 1, 32 and 33 also include two craters of hazardous size (0.7 meter diameter) which were intentionally located directly tangent with the front wheel surface tracks. These are included to illustrate the appearance of these craters exactly at the moment when a command to stop the vehicle must be sent without any further delay in order to prevent the vehicle from driving into the crater.

These figures illustrate the geometrical limit on vehicle velocity as discussed earlier in Section II. A. 2. f.

For the assumed camera height (2 meters), minimum recognition angle (1°), system delay (10 seconds), and hazardous crevasse size (≥ 0.7 meter), the hazardous crevasse detection lines have been located in these figures. Figures 30, 31 and 1 show that the crevasses are nearer to the viewer than are the detection lines, meaning that the crevasses would have been recognized as hazardous at an earlier time and a command decision exercised to avoid them.

However, Figures 32 and 33 show that the projected vehicle image is located more distant than the detection lines. This means that the driver would not have yet recognized the crevasses as hazardous when the vehicle would start driving into these crevasses.

Therefore, since Figures 32 and 33 represent projected vehicle images for 3 and 4 KM/hour velocities respectively, the assumed geometry limits the maximum speed to < 3 KM/hour as confirmed earlier by a computer run in Section II. A. 2. f.

IV. D. 3 Parameter Values Used for the Sample Case

a. Vehicle Dimensions - JPL vehicle dimensions except that the camera is chosen to be located 2 meters above a flat surface:

D_1 through D_{11} are dimensioned as shown in Figure 34 of IV. E except $D_{10} = (2-D_1)$ meters.

b. General Parameters:

PDLY = 6 sec.

TMDLY = 1.3 sec.

CMDLY = 4 sec.

HFOV = 60°

VFOV = 40°

CS = 0.7 M.

RA = 1°

JSH = as shown versus time in Appendix F.

RVCIPS = 10" = $\frac{10}{39.37}$ meters (max. height of calcomp plot)

TMR = 4 samples/second

c. Telemetry and Command Requirements:

As shown versus time in Appendix F.

d. Crater Field and Horizon Line Dimensions (all in meters)

1) Horizon Line

X = 2300

Y = -N to +N

$\Delta = 10^{-3}$

$$Z = (500)\left(e^{-\frac{|Y|}{100}}\right)\left(\frac{\sin 20\pi Y}{\pi Y}\right)$$

2) 70 cm Craters

$(X-h)^2 + (Y-K)^2 = (0.35)^2$, Z=0

h = as defined later

K = + 1, - 1

3) Crater Field (at t_o -88 sec for 1.8 meter/sec. velocity)

$(X-h)^2 + (Y-K)^2 = R^2$, Z=0

h	K	R	h	K	R	h	K	R
19	-5	1.5	13	6	0.1	24	-3	0.1
14	-4	1.2	15	-1	0.2	24	2	0.1
20	+1	.35	15	+2	0.2	25	2	0.2
20	-1	.35	16	9	0.1	26	-6	0.2
27	+11	8	17	3	0.2	26	-4	0.2
23	-5	0.6	17	6	0.1	27	-4	0.1
28	+1	1.0	19	-3	0.2	27	-2	0.1
25.5	0	0.5	19	4	0.1	28	-5	0.1
29	-2	0.5	18	-1	0.1	29	-7	0.2
17	-20	10	18	+1	0.2	30	-4	0.2
15	6	0.5	20	+3	0.1	31	-5	0.1
8	-1	0.1	21	-3	0.1	31	-7	0.2
9	0	0.1	21	-2	0.1	13	0	0.2
11	0	0.1	22	-3	0.2	14	0	0.2
11	-1	0.1	22	4	0.2	14	1	0.2
12	4	0.1	23	3	0.1	14	2	0.2
						15	1	0.2

4) Crater Field (at t_o + X sec.)

Same as 3, but subtract (88 + X)(1/8) = S meters from each value of "h"

AT 1/8 METER/SEC, WITH ONLY TV AVAILABLE FOR CREVASSE DETECTION

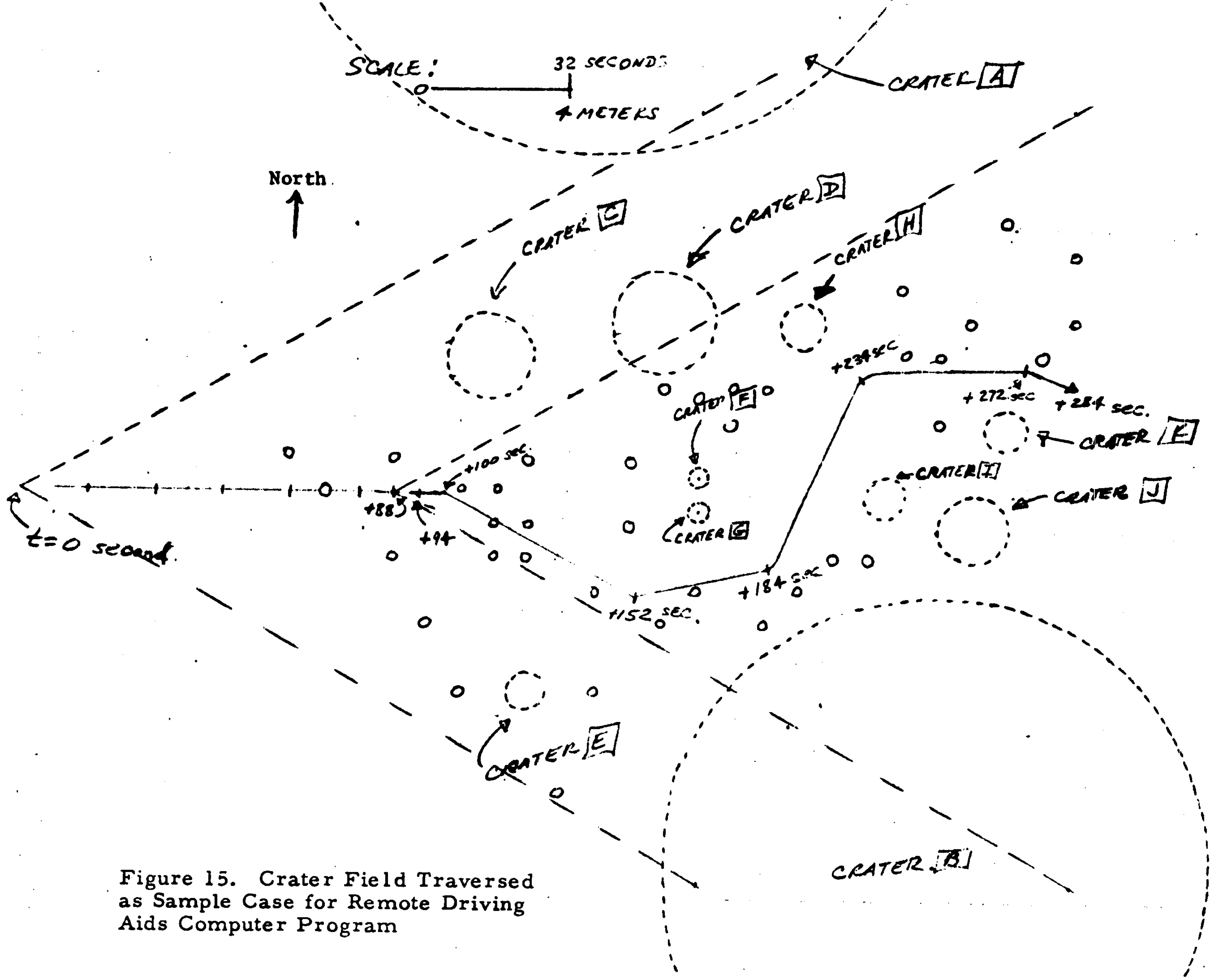


Figure 15. Crater Field Traversed as Sample Case for Remote Driving Aids Computer Program

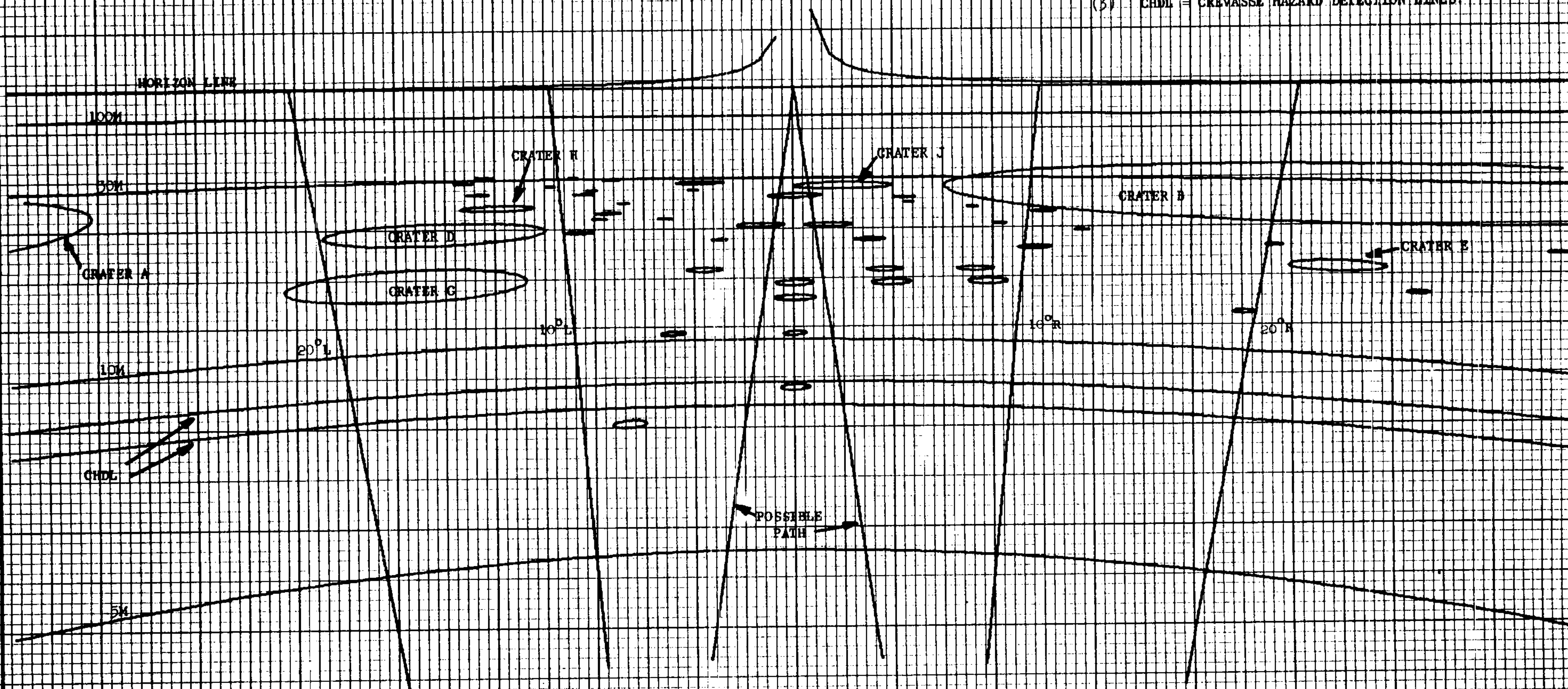


Figure 16.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH 0° HEADING (DUE EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION WHEN CAMERA EXPOSURE PERIOD BEGAN.

(3) CHDL = CREVASSE HAZARD DETECTION LINES

Figure 17.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH -40° HEADING AT THE VERTICAL CENTERLINE (40° NORTH OF EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION WHEN CAMERA EXPOSURE PERIOD BEGAN.

(3) CHDL - CREVASSE HAZARD DETECTION LINES.

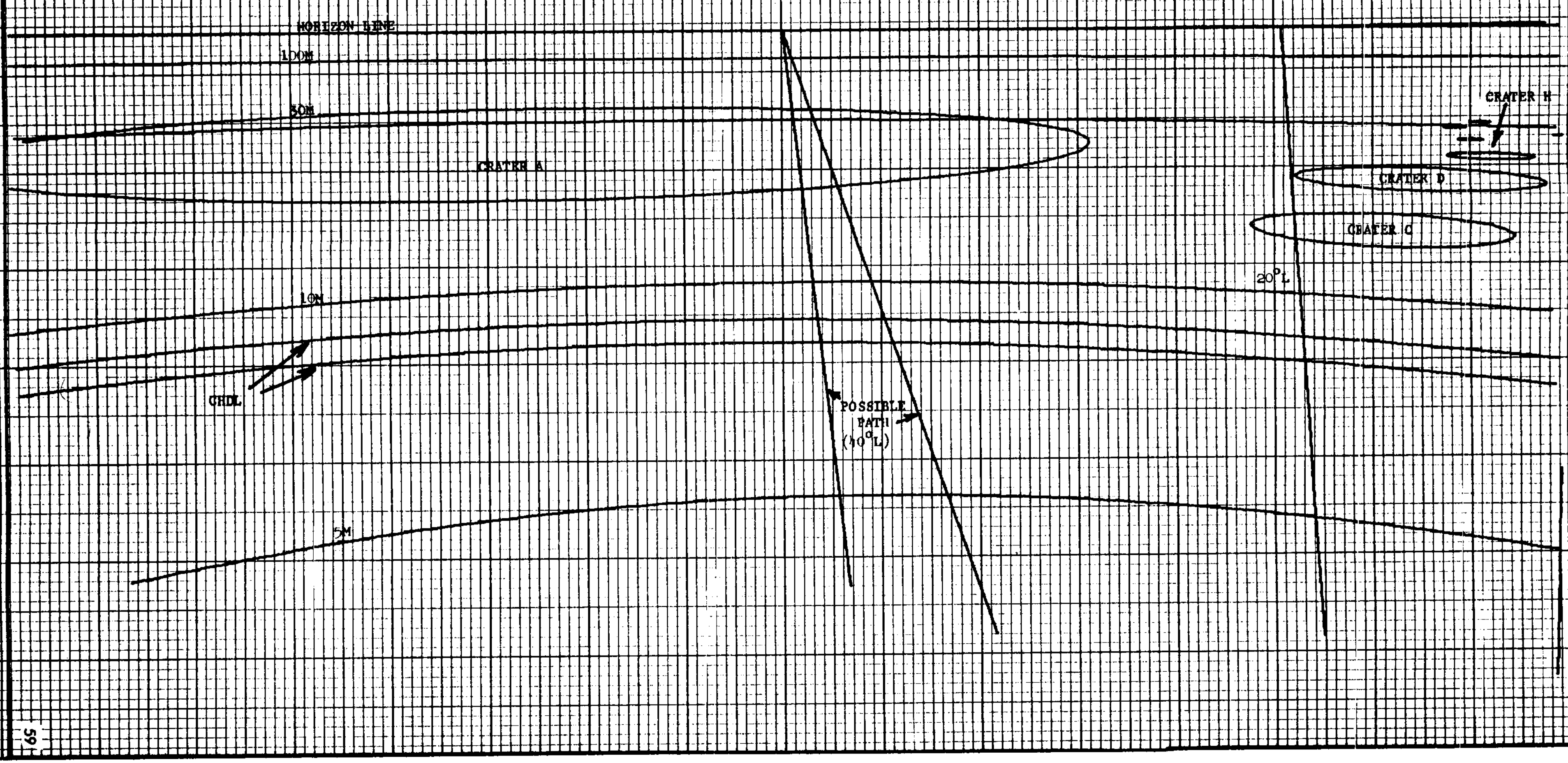
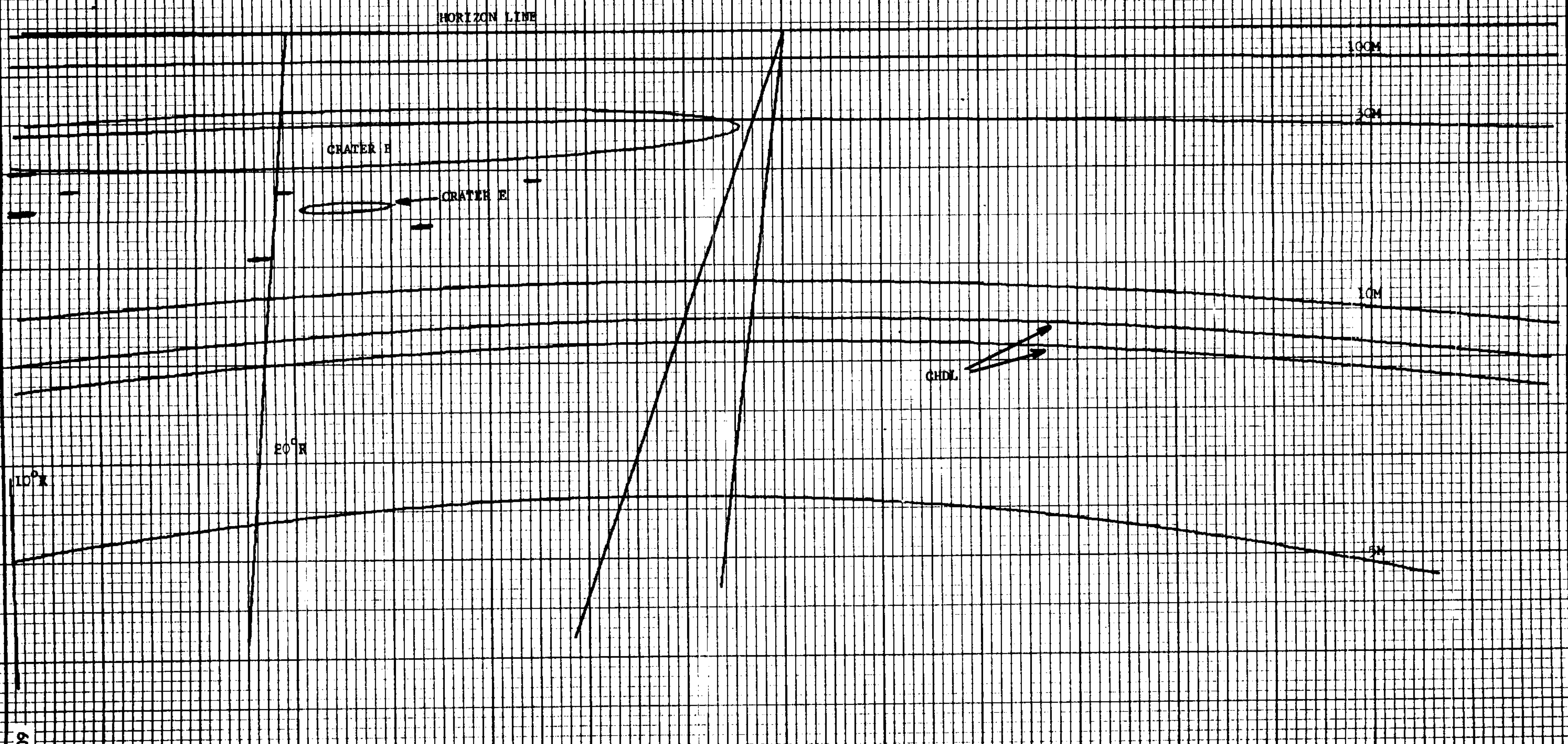


Figure 18.

(1) View from t = 0 second location looking at crater field with +40° heading (40° South of East).

(2) Grid system centered on point midway between vehicle front wheels location when camera exposure period began.

(3) CHDL - crevasse hazard detection lines.



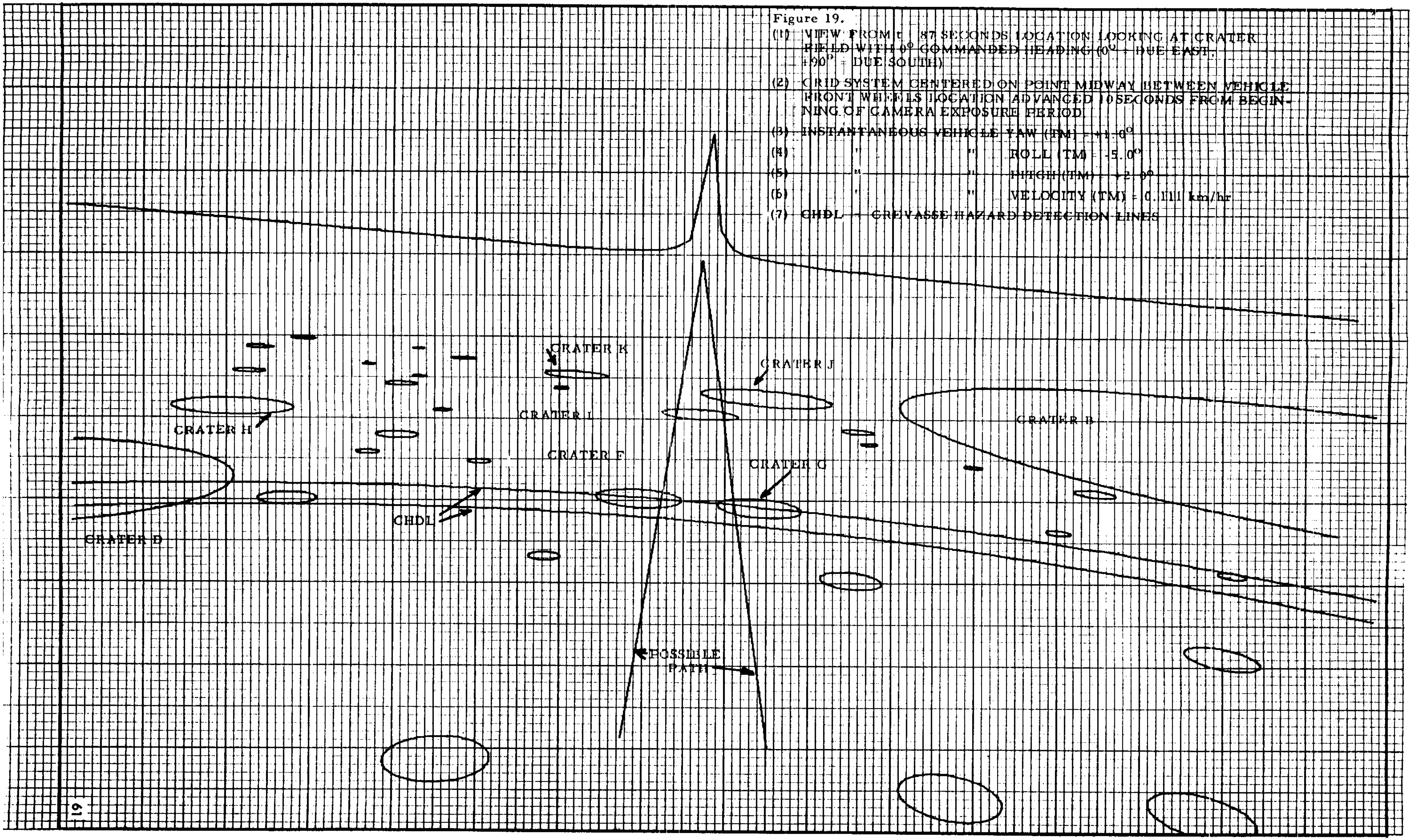


Figure 19.

(1) VIEW FROM t 87 SECONDS LOCATION LOOKING AT CRATER FIELD WITH 0° COMMANDED HEADING (0° = DUE EAST, +90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD

(3) INSTANTANEOUS VEHICLE YAW (TM) = +1.0°

(4) " " ROLL (TM) = -5.0°

(5) " " PITCH (TM) = +2.0°

(6) " " VELOCITY (TM) = 0.111 km/hr

(7) CHDL — CREVASSE HAZARD DETECTION LINES

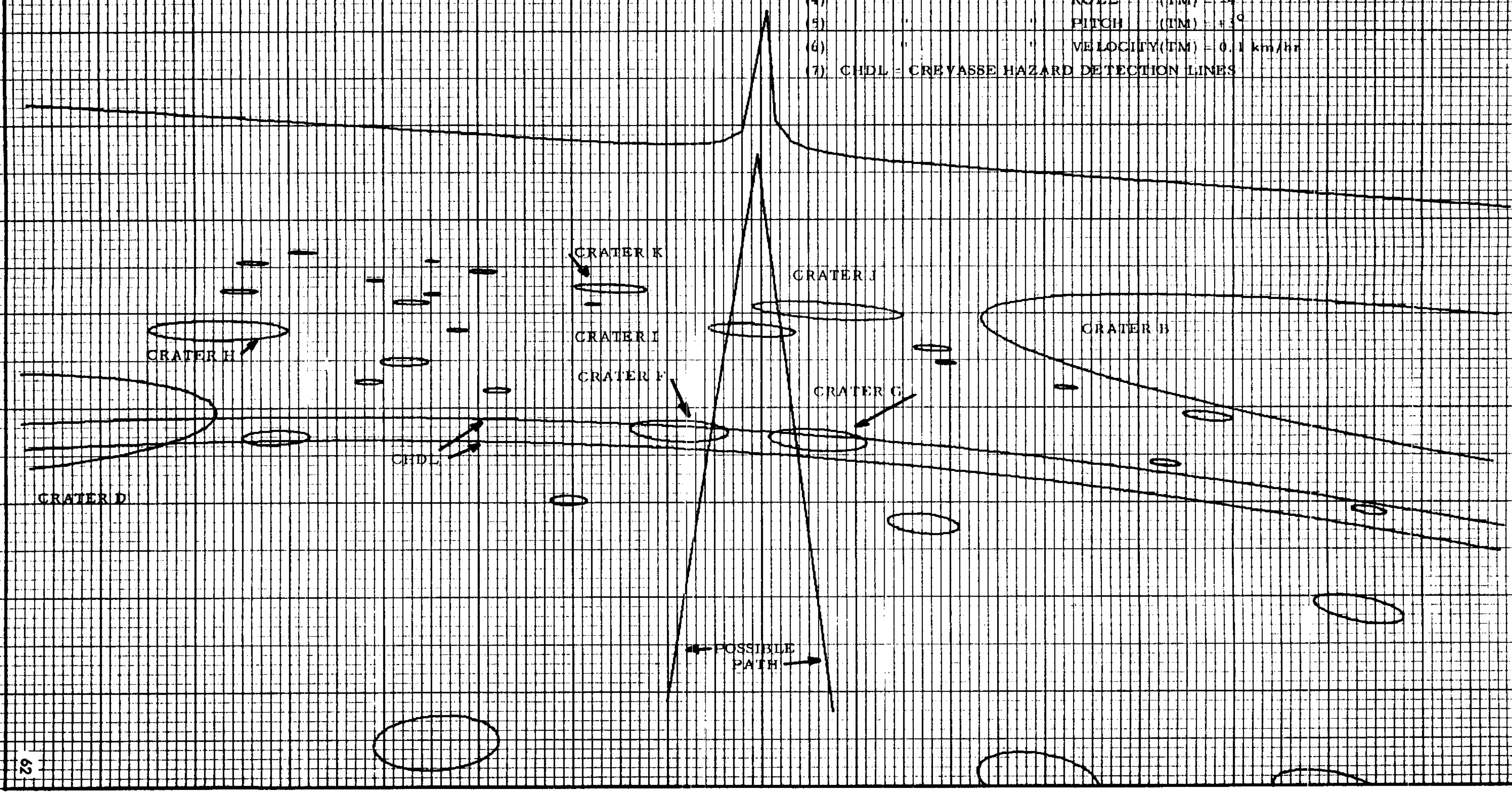


Figure 20.

(1) VIEW FROM 88 SECONDS LOCATION LOOKING AT CRATER FIELD WITH 0° COMMANDED HEADING (0° = DUE EAST; + 90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = 0°

(4) " " ROLL (TM) = -4°

(5) " " PITCH (TM) = +3°

(6) " " VELOCITY(TM) = 0.1 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

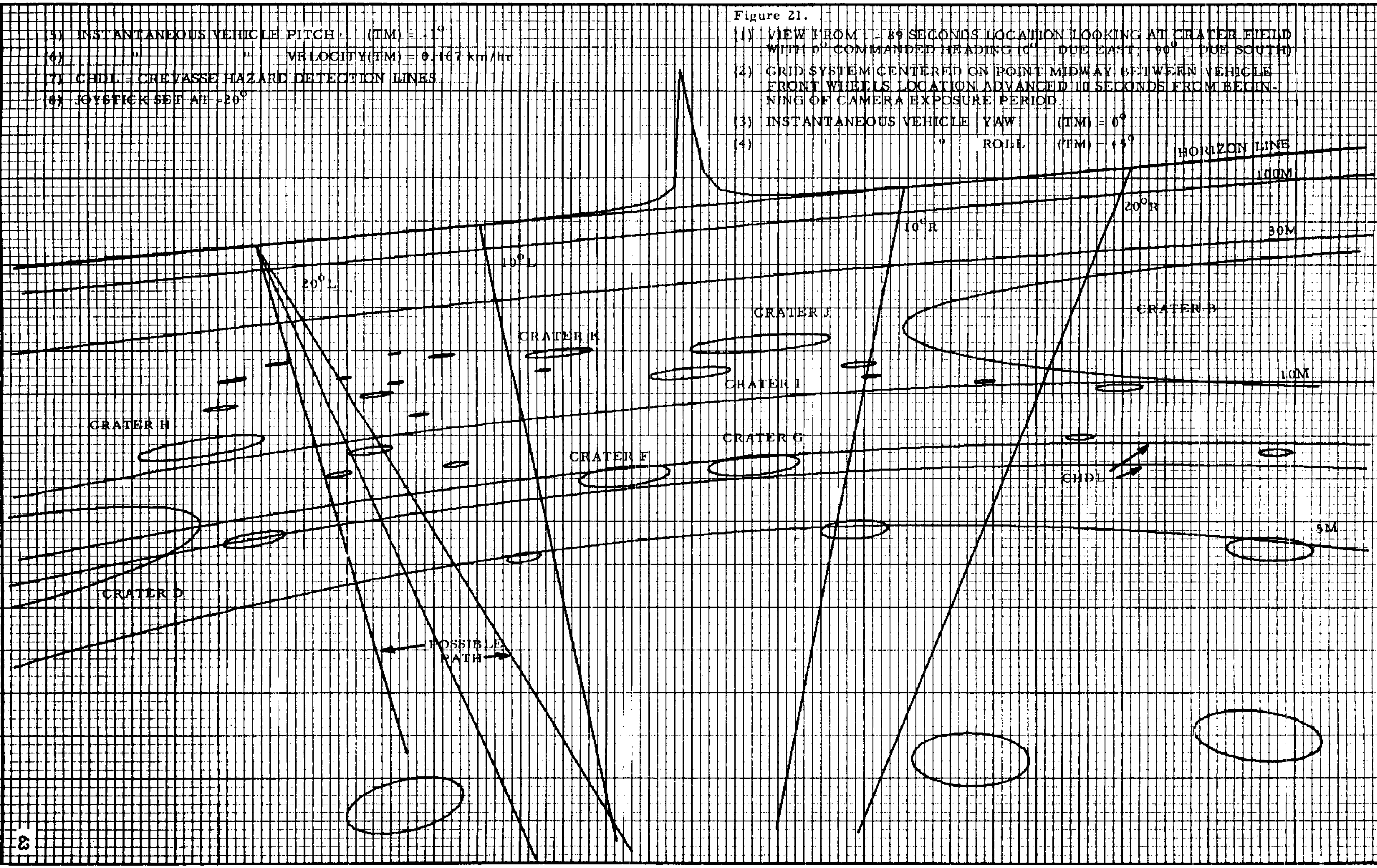


Figure 21.

(1) VIEW FROM - 89 SECONDS LOCATION LOOKING AT CRATER FIELD WITH 0° COMMANDED HEADING (0° = DUE EAST, 90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = 0°

(4) " " ROLL (TM) = +5°

(5) INSTANTANEOUS VEHICLE PITCH (TM) = -1°

(6) " " VELOCITY(TM) = 0.167 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) JOYSTICK SET AT -20°

Figure 22.

(1) VIEW FROM t = 90 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; +90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = -3°

(4) " " ROLL (TM) = +10°

(5) " " PITCH (TM) = +5°

(6) INSTANTANEOUS VEHICLE VELOCITY (TM) = 0.167 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) JOYSTICK SET AT +28° AND HEADING COMMAND EXECUTED AT t = 96 SECONDS

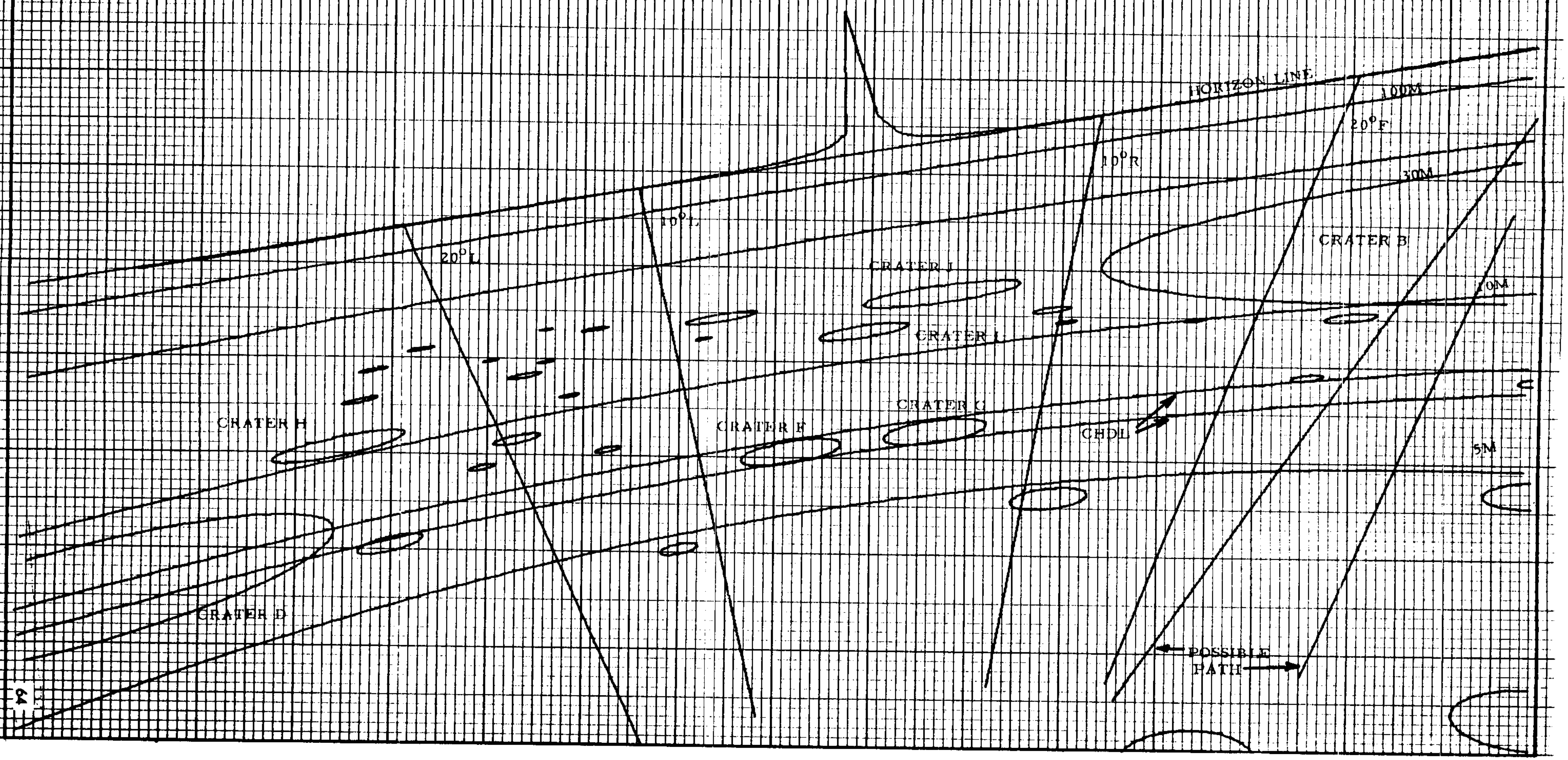


Figure 23.

(1) VIEW FROM t = 92 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; $+90^\circ$ = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = $+1^\circ$

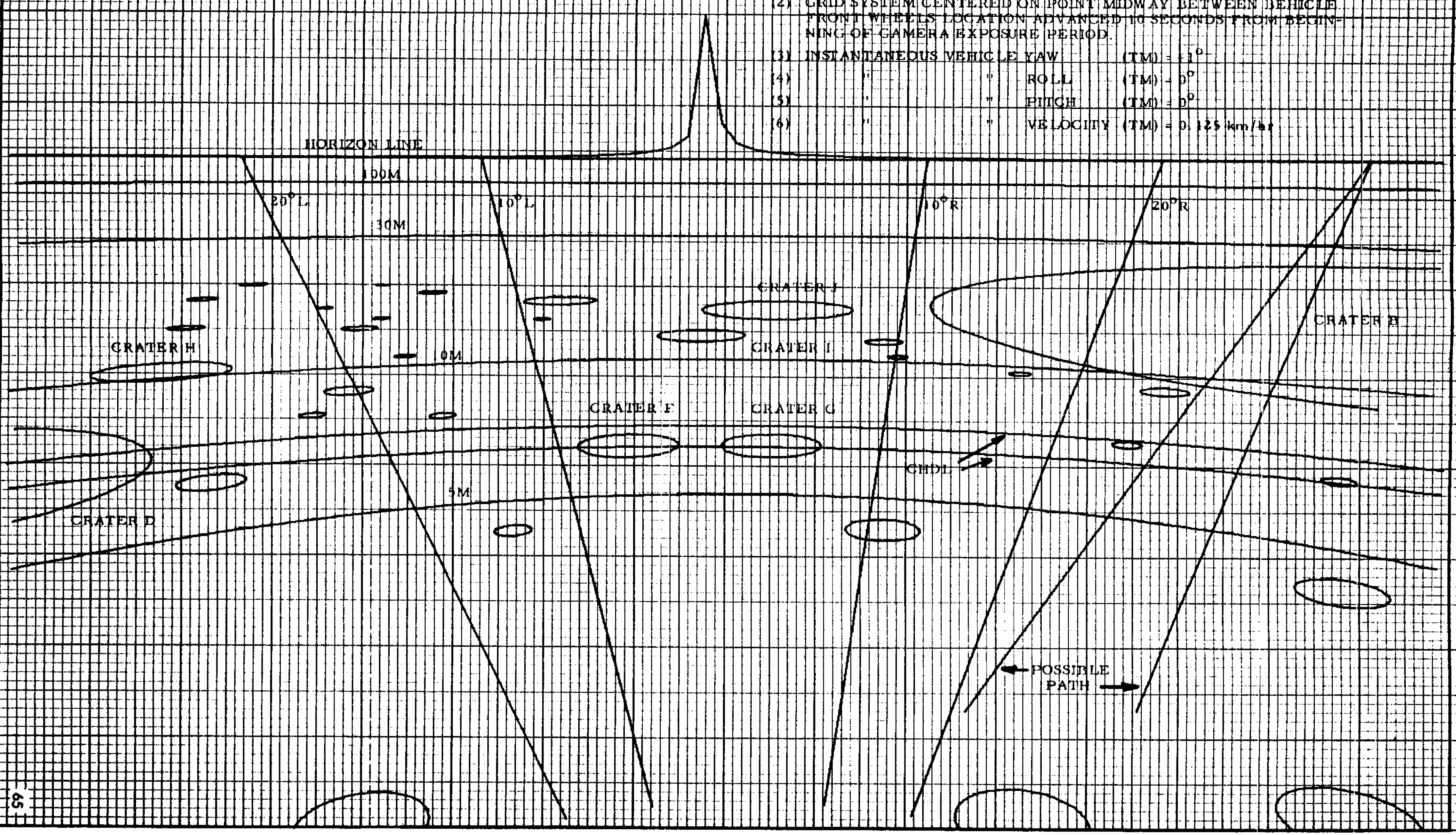
(4) " " ROLL (TM) = 0°

(5) " " PITCH (TM) = 0°

(6) " " VELOCITY (TM) = 0.125 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH.



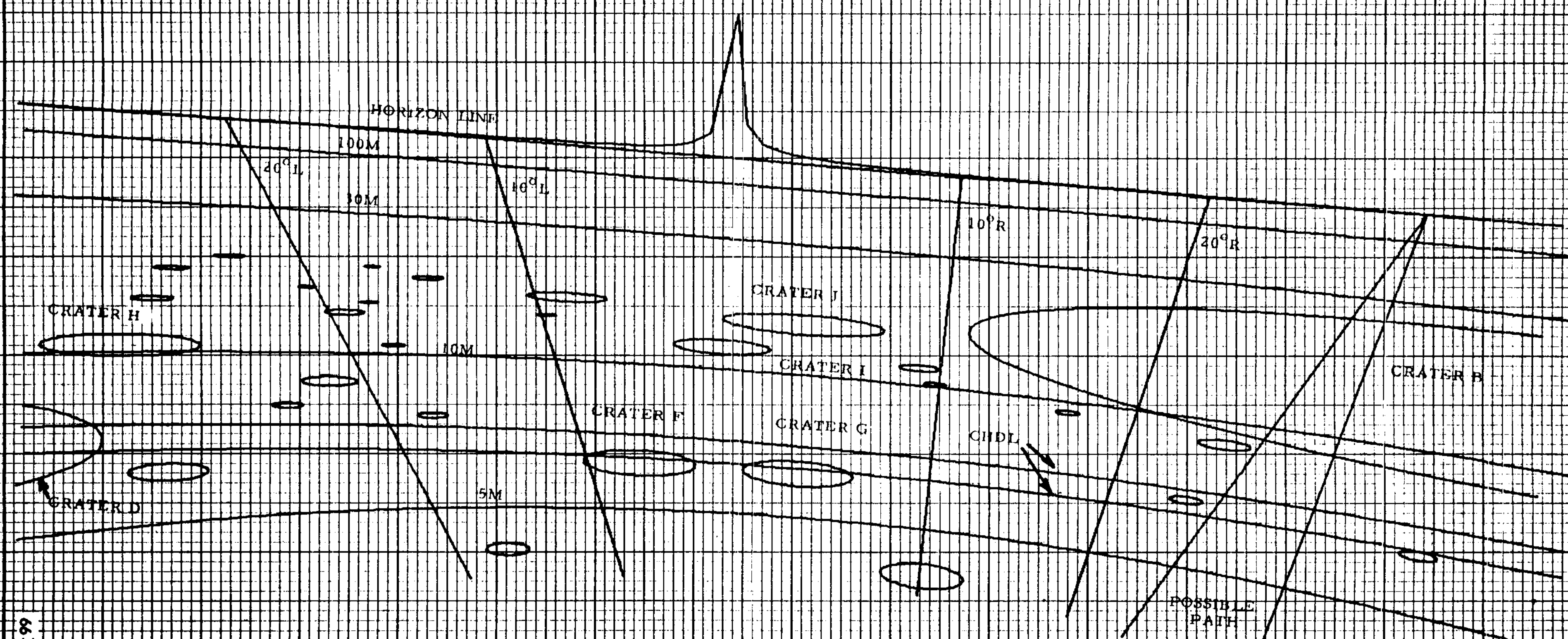


Figure 24.

(1) VIEW FROM t = 94 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; 90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCE 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = +2°

(4) " " ROLL (TM) = -5°

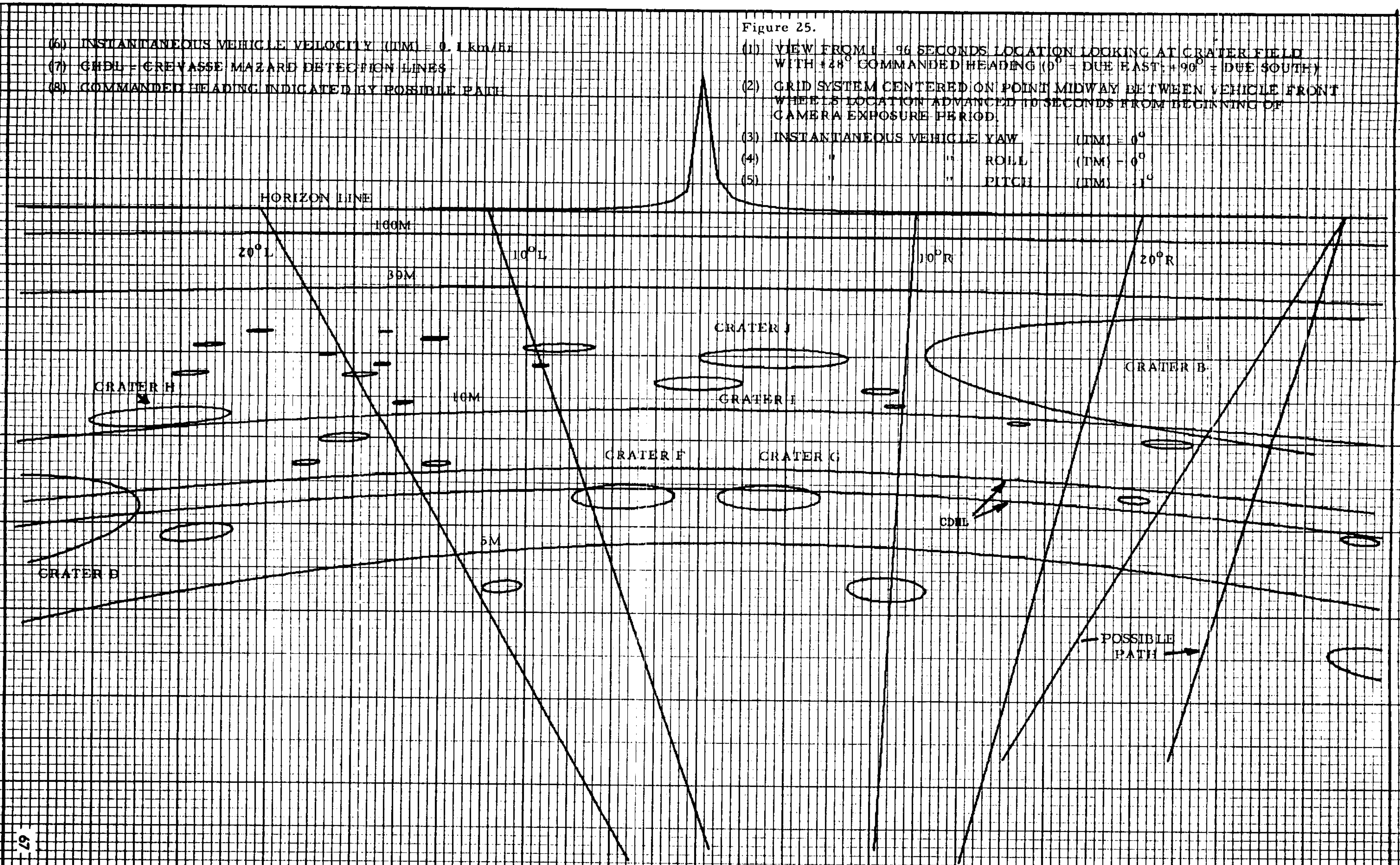
(5) " " PITCH (TM) = +10°

(6) " " VELOCITY (TM) = 0.125 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH.

Figure 25.


(1) VIEW FROM t = 96 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; +90° = DUE SOUTH)
(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.
(3) INSTANTANEOUS VEHICLE YAW (TM) = 0°
(4) " " ROLL (TM) - 0°
(5) " " PITCH (TM) 1°
(6) INSTANTANEOUS VEHICLE VELOCITY (TM) = 0.1 km/hr
(7) CHDL = CREVASSE HAZARD DETECTION LINES
(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH
HORIZON LINE
100M
30M
10M
5M
20° L
10° L
10° R
20° R
CRATER J
CRATER B
CRATER H
CRATER I
CRATER F
CRATER G
CRATER D
CDHL
POSSIBLE PATH

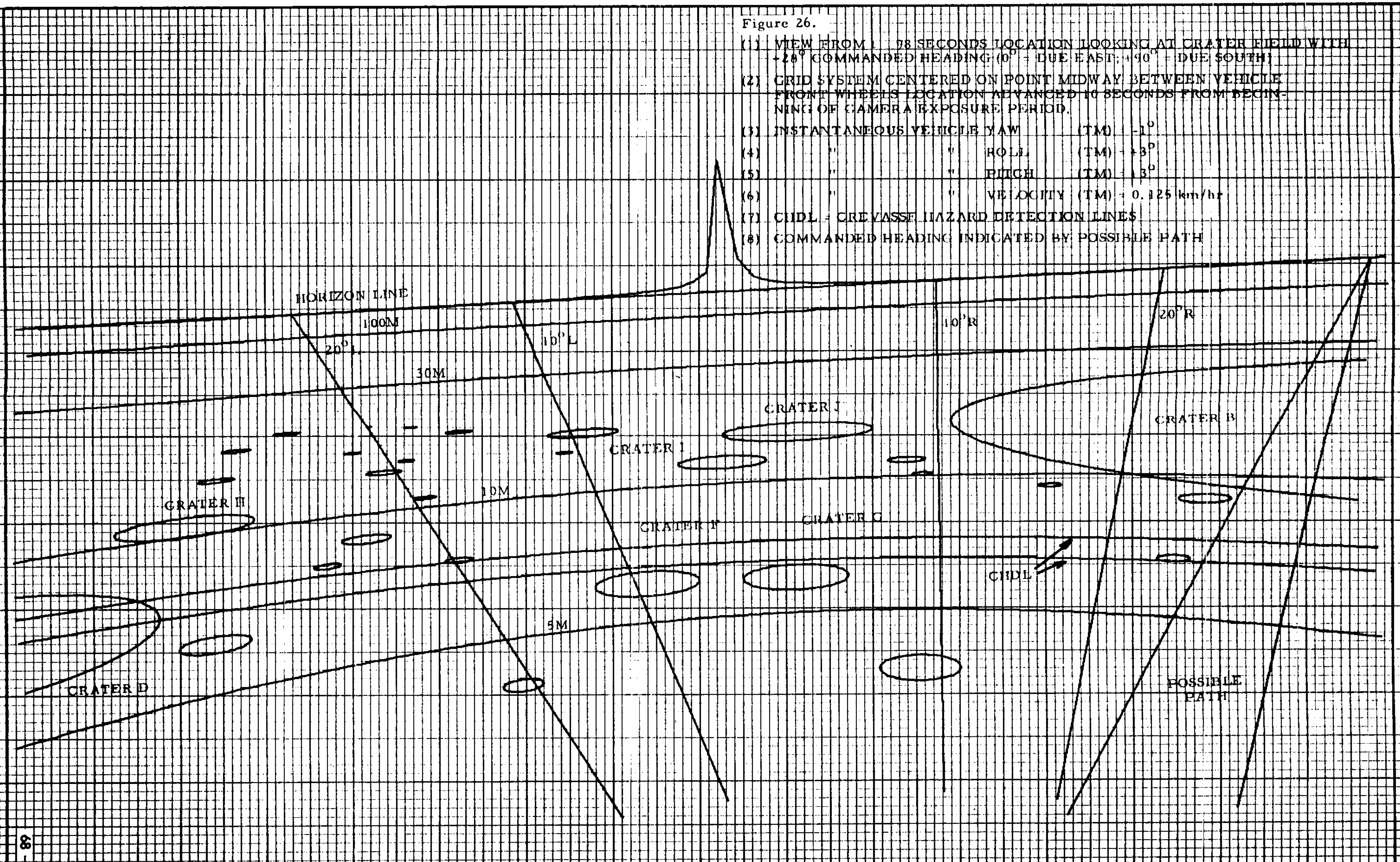


Figure 26.

(1) VIEW FROM 1 78 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; +90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) -1°

(4) " " ROLL (TM) +3°

(5) " " PITCH (TM) +3°

(6) " " VELOCITY (TM) = 0.125 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH

Figure 27.

(1) VIEW FROM 1 - 100 SECONDS LOCATION LOOKING AT CRATER FIELD WITH 128° COMMANDED HEADING (0° = DUE EAST; 90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = +5°

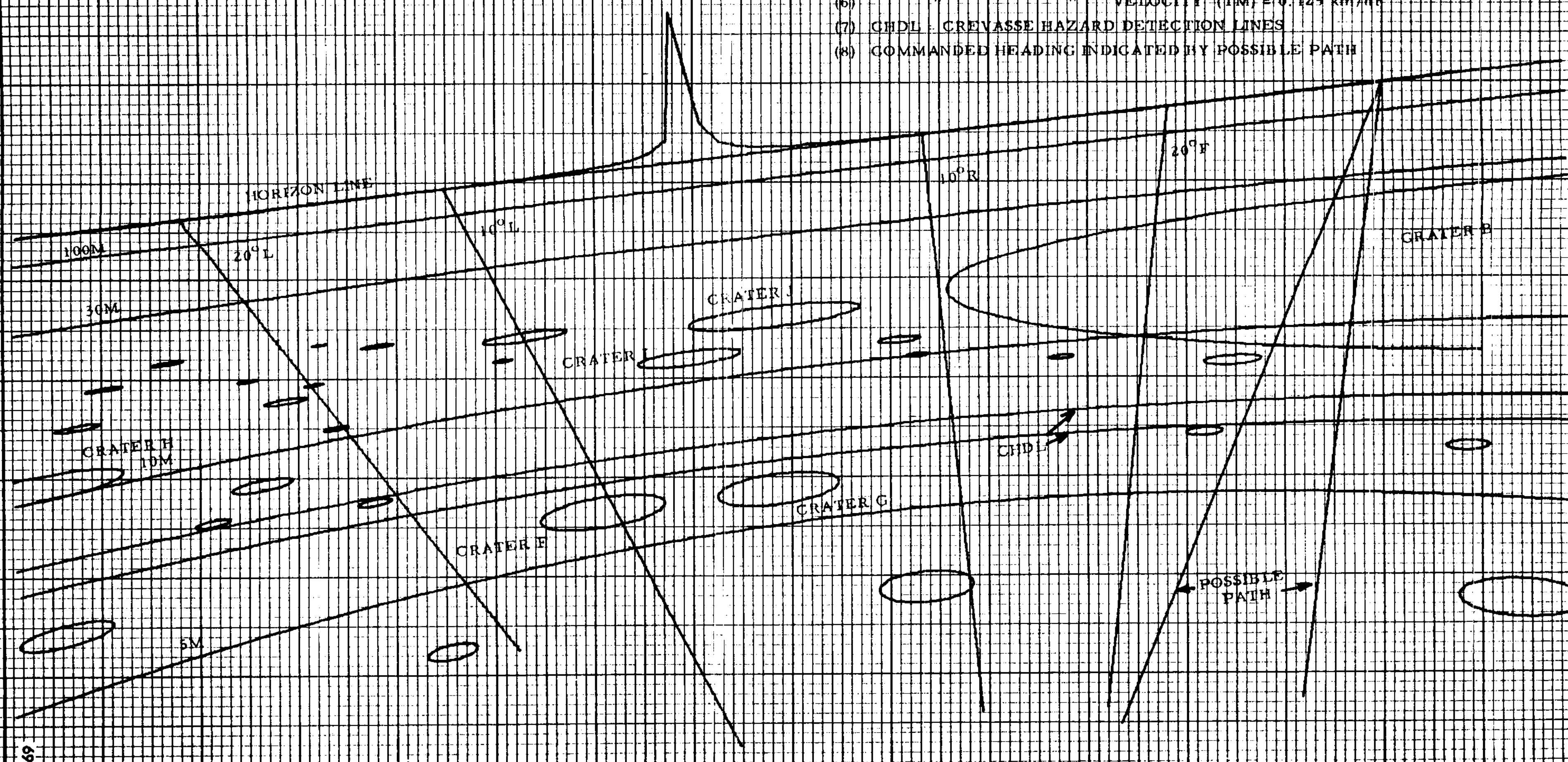
(4) " " ROLL (TM) = +6°

(5) " " PITCH (TM) = +5°

(6) " " VELOCITY (TM) = 0.125 km/hr

(7) CHDL : CREVASSE HAZARD DETECTION LINES

(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH



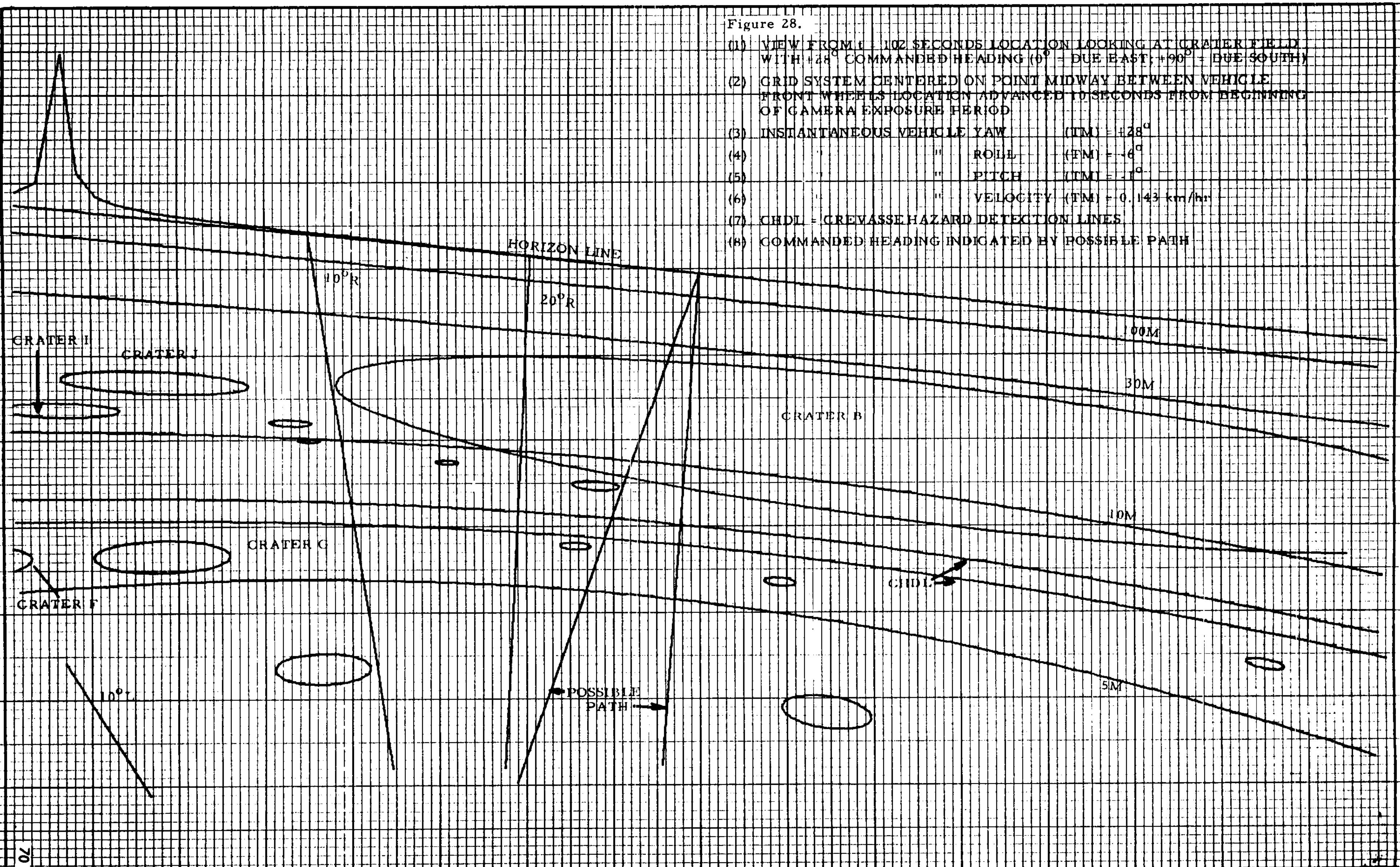


Figure 28.

(1) VIEW FROM t = 102 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; +90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD

(3) INSTANTANEOUS VEHICLE YAW (TM) = +28°

(4) " ROLL (TM) = -6°

(5) " PITCH (TM) = -1°

(6) " VELOCITY (TM) = 0.143 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH

11

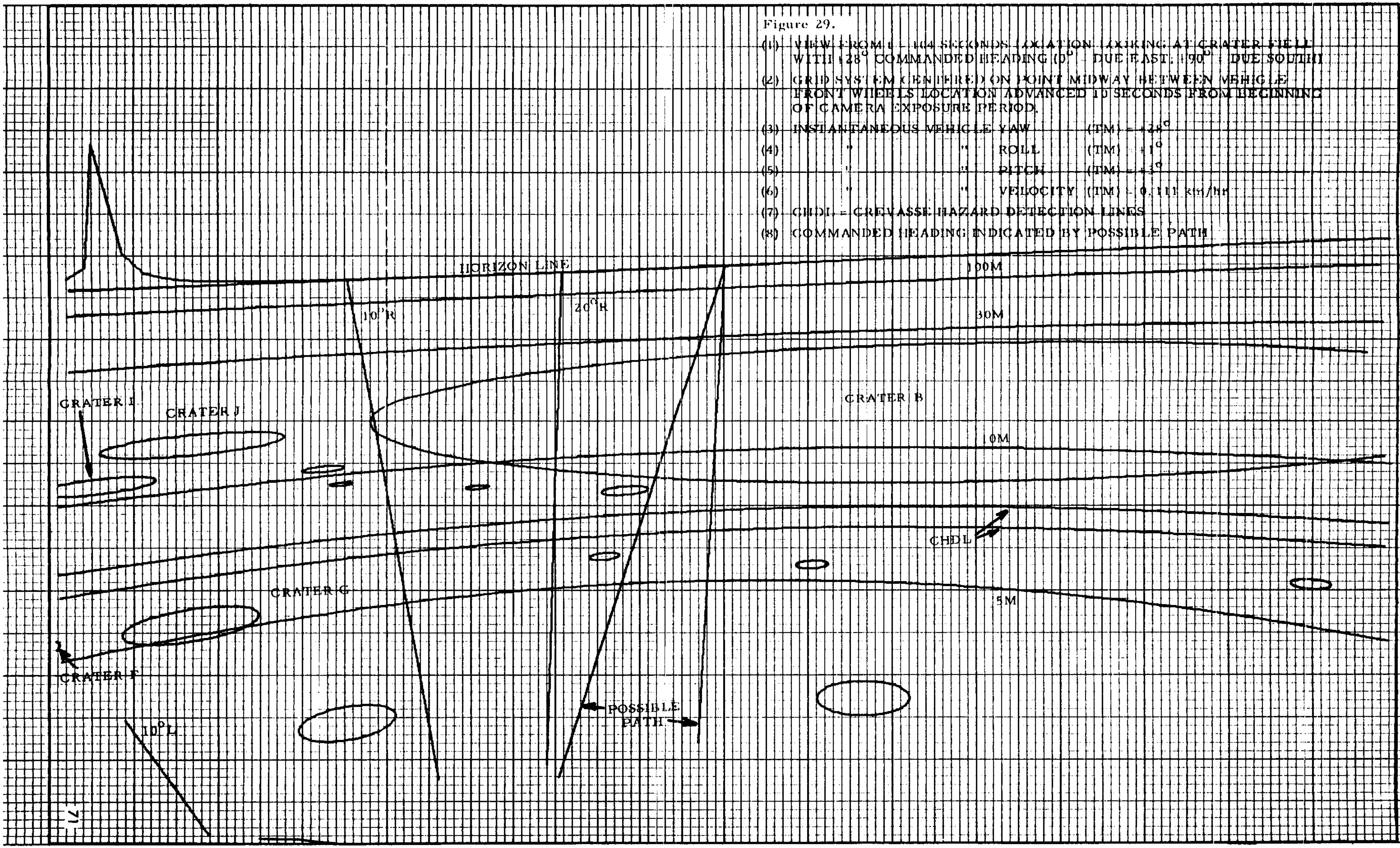


Figure 29.

(1) VIEW FROM t = 104 SECONDS LOCATION LOOKING AT CRATER FIELD WITH +28° COMMANDED HEADING (0° = DUE EAST; +90° = DUE SOUTH)

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) INSTANTANEOUS VEHICLE YAW (TM) = +28°

(4) " " ROLL (TM) = +1°

(5) " " PITCH (TM) = +3°

(6) " " VELOCITY (TM) = 0.111 km/hr

(7) CHDL = CREVASSE HAZARD DETECTION LINES

(8) COMMANDED HEADING INDICATED BY POSSIBLE PATH

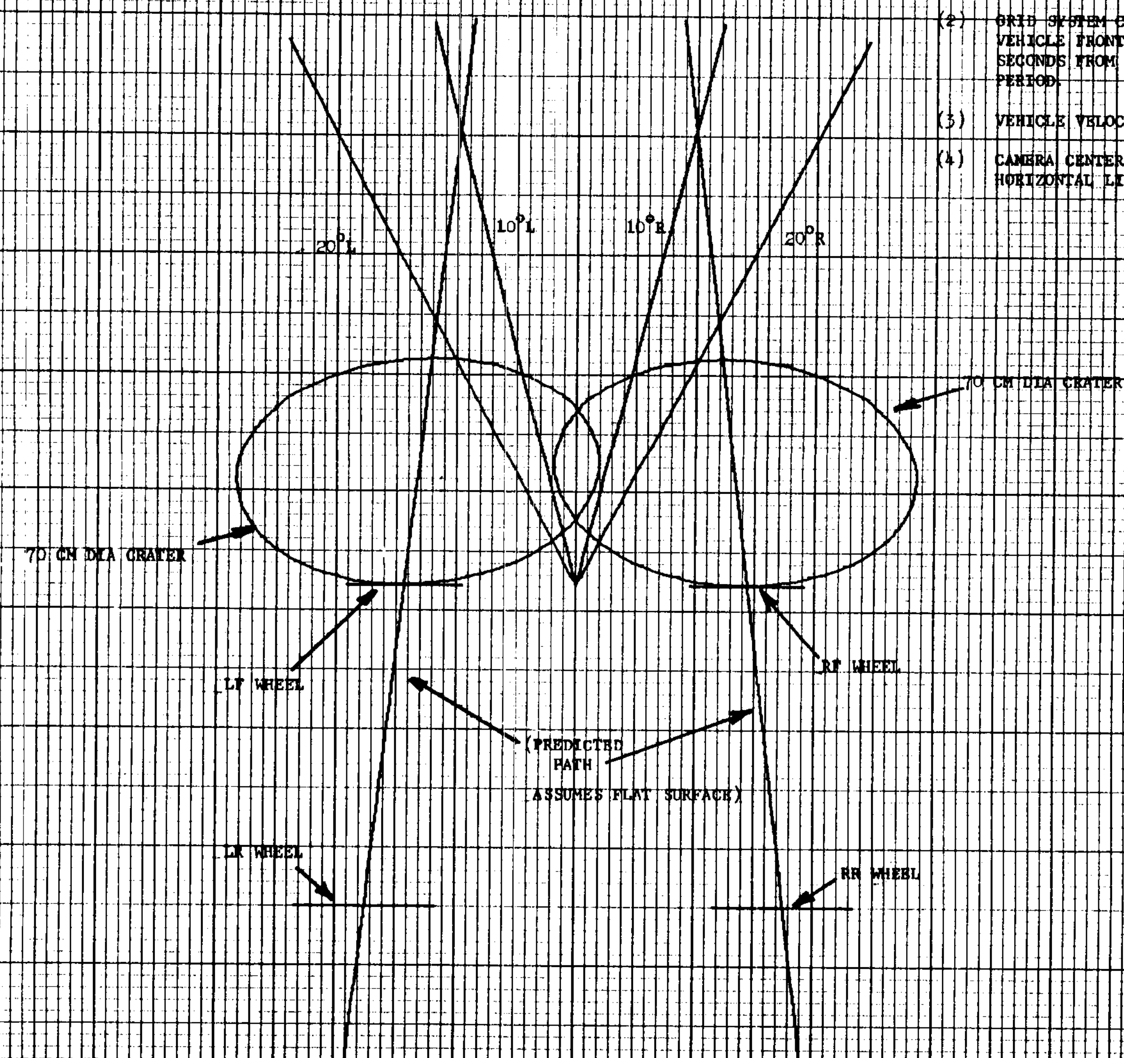


Figure 30.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH 0° HEADING (DUE EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) VEHICLE VELOCITY = $^{1}/_{2}$ $^{KM}/_{HR}$.

(4) CAMERA CENTERLINE FOV IS 40° DOWN FROM HORIZONTAL LINE-OF-SIGHT.

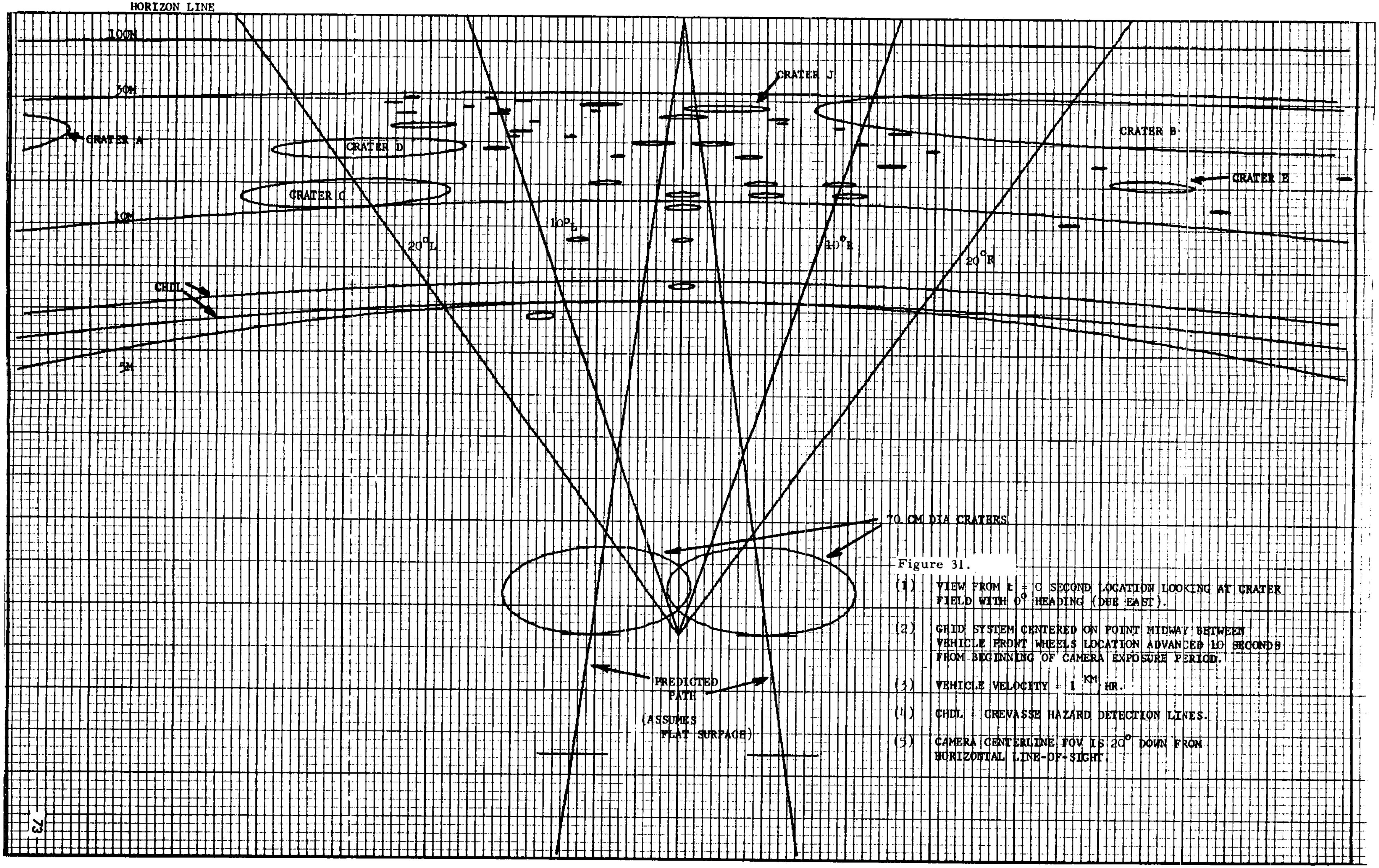


Figure 31.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH 0° HEADING (DUE EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) VEHICLE VELOCITY = 1 KM/HR.

(4) CHDL - CREVASSE HAZARD DETECTION LINES.

(5) CAMERA CENTERLINE FOV IS 20° DOWN FROM HORIZONTAL LINE-OF-SIGHT.

Figure 32.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH 0° HEADING (DUE EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) VEHICLE VELOCITY = 3 KM/HR.

(4) CHDL - CREVASSE HAZARD DETECTION LINES.

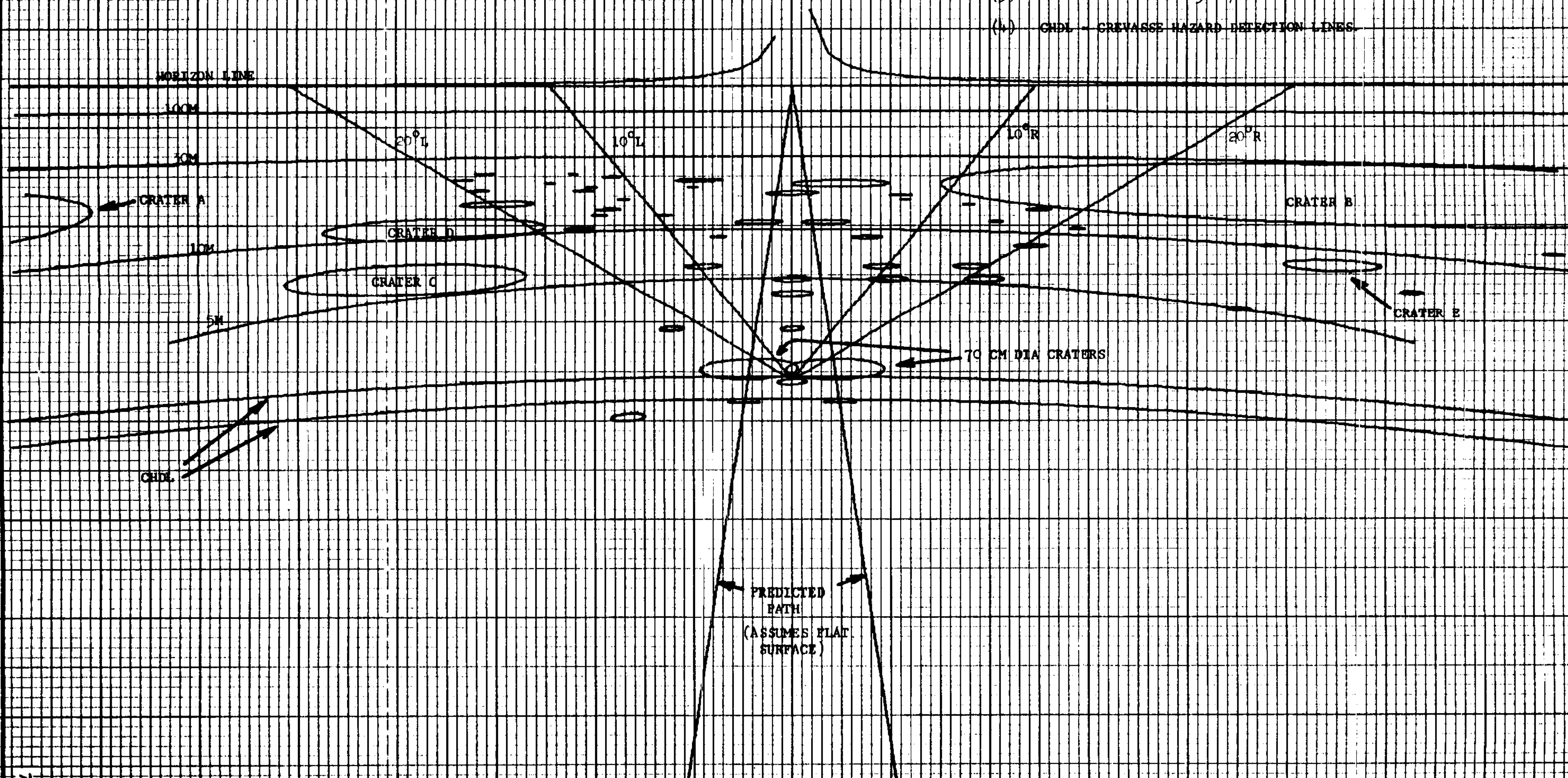


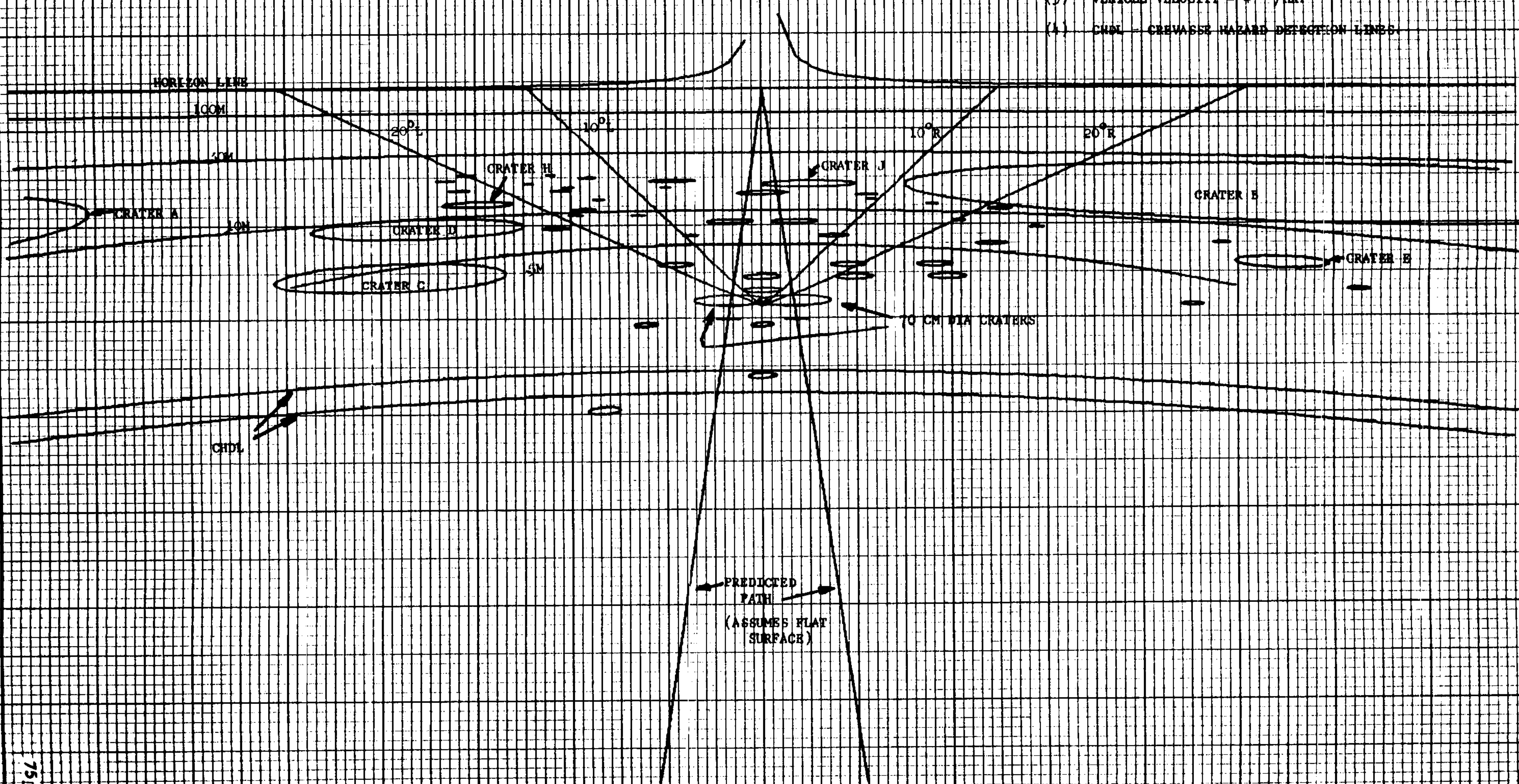
Figure 33.

(1) VIEW FROM t = 0 SECOND LOCATION LOOKING AT CRATER FIELD WITH 0° HEADING (DUE EAST).

(2) GRID SYSTEM CENTERED ON POINT MIDWAY BETWEEN VEHICLE FRONT WHEELS LOCATION ADVANCED 10 SECONDS FROM BEGINNING OF CAMERA EXPOSURE PERIOD.

(3) VEHICLE VELOCITY = 4 KM/HR.

(4) CHDL - CREVASSE HAZARD DETECTION LINES.



IV. E. Application of Driving Aids to Overlay for Use with JPL Vehicle

1. Introduction

Concurrent with the development of the general computer program described previously, an abbreviated computer program was developed for use in calculating and producing driving aids as they appear for a fixed application – the JPL vehicle. The JPL vehicle dimensions are as shown in Figure 34.

Since the vehicle has no means of telemetering information, is fixed in velocity (0.675 mph), would have a camera mounted in a fixed orientation, and would be assumed to be driven on a flat surface, the driving aids would appear fixed on a TV display. Therefore, it was decided that the practical presentation of the driving aids would be on a transparent overlay for use with the TV display. These cases were run during the latter part of the contract period. Case I, II, and III overlays are Figures 35, 36, and 37, respectively. Description of the cases appear in IV.E.3.

2. Mathematical Representation in the Surface Coordinate System

a. Translation-Transformation System:

$$\left.\begin{matrix} X_A \\ Y_A \\ Z_A \end{matrix}\right\} =$$

Coordinates of point(s) in surface axes coordinate system – defined here as having its origin at a flat surface subpoint of the camera axes system origin. (Reference: Figure 34A and 34B)

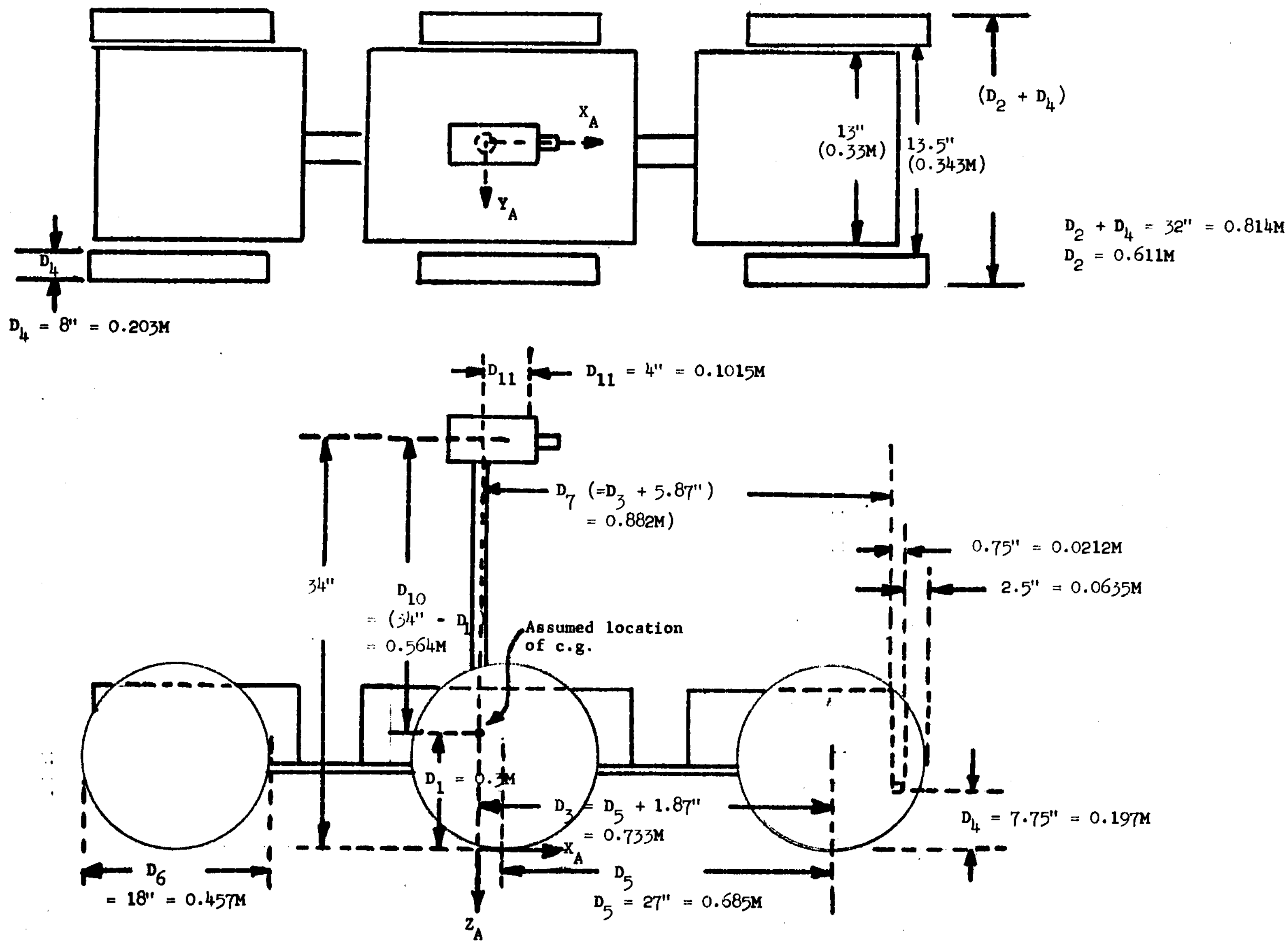
Using the dimensions from Figure 34:

$$\left.\begin{matrix} X_B = X_A \\ Y_B = Y_A \\ Z_B = Z_A + 34'' \end{matrix}\right\}$$

Coordinates of point(s) after translation to focal point axes coordinate system prior to any camera orientation.

$$\begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{pmatrix}}_{Y\ (\text{Elevation})} \underbrace{\begin{pmatrix} \cos\epsilon & \sin\epsilon & 0 \\ -\sin\epsilon & \cos\epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{Z\ (\text{Azimuth})} \begin{pmatrix} X_B \\ Y_B \\ Z_B \end{pmatrix}$$

Where X_C, Y_C, Z_C are coordinates of point(s) after camera orientation.



a) Top View of JPL Vehicle

b) Side View of JPL Vehicle

Figure 34. Views and Dimensions of JPL Vehicle (Not to Scale)

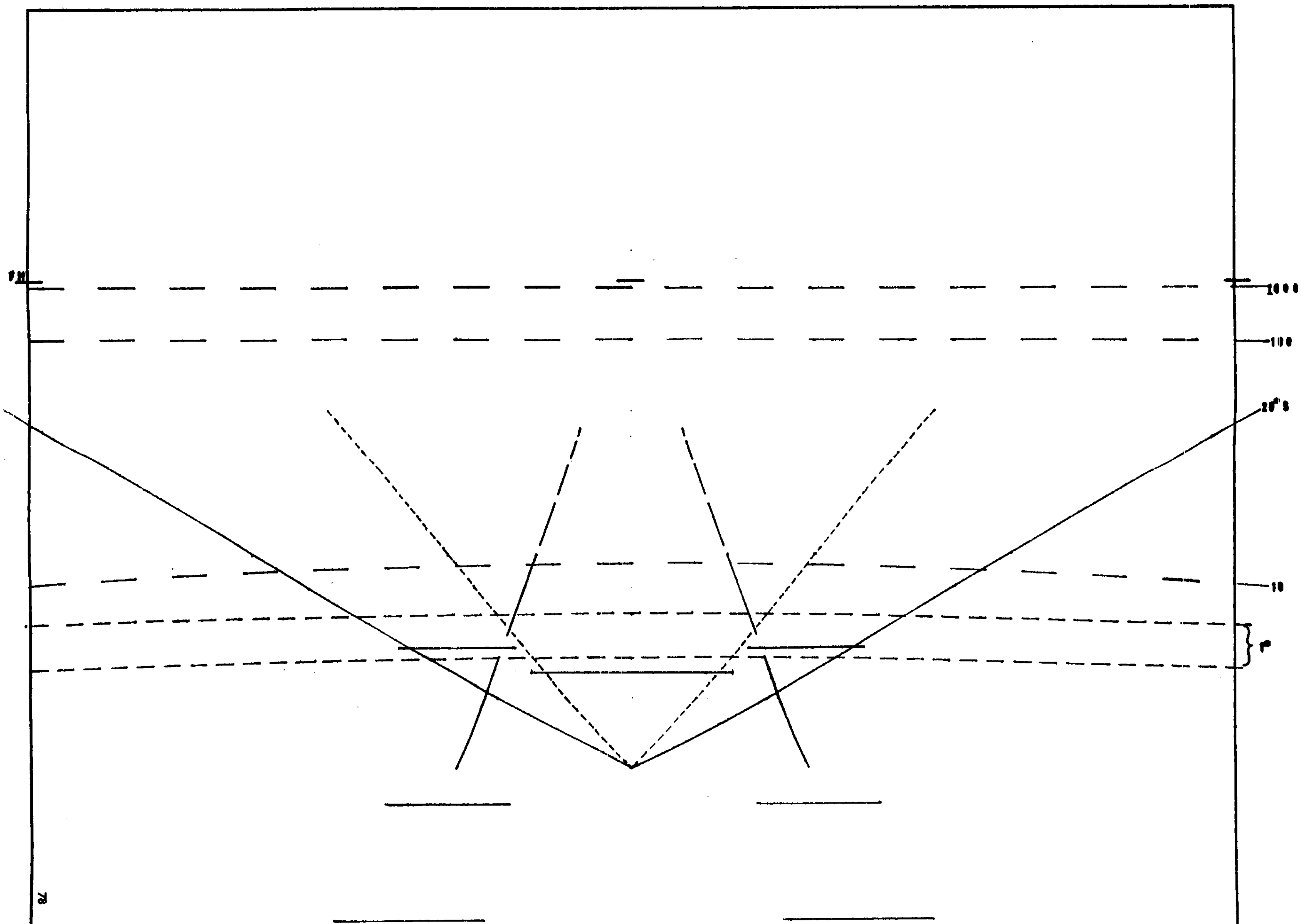


Figure 35. TV Overlay Constructed From Output of Case 1 Computer Program for Use With JPL Vehicle

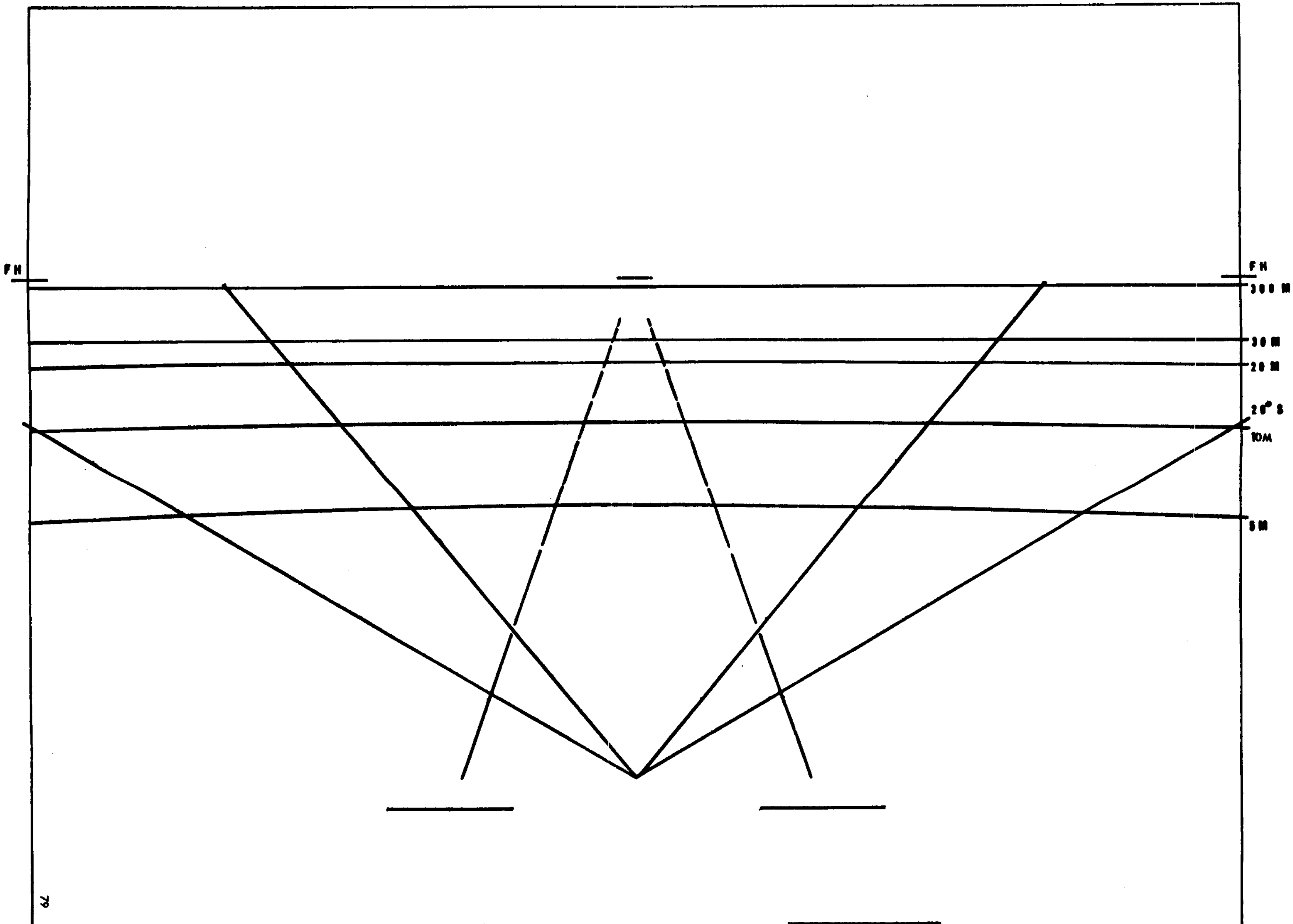


Figure 36. TV Overlay Constructed From Output of Case 2 Computer Program for Use With JPL Vehicle

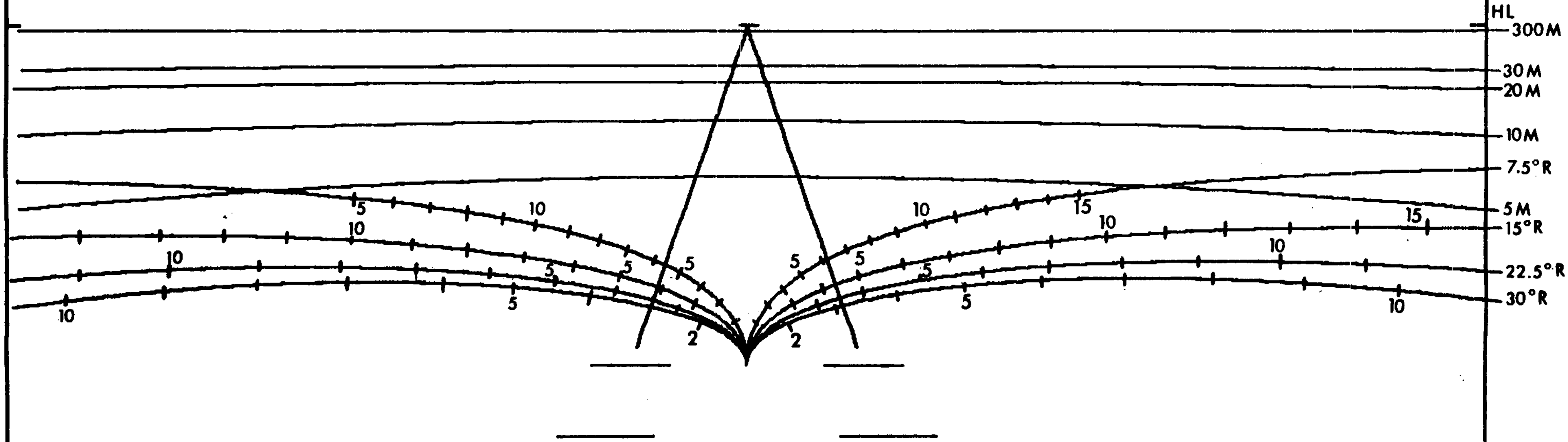


Figure 37. TV Overlay Generated by Case 3 Computer Program for Use With JPL Vehicle

$$\left.\begin{aligned} \tan \beta_C &= \frac{Y_C}{X_C} \\ \tan \alpha_C &= \frac{Z_C}{X_C} \end{aligned}\right\}$$

solves for elevation and azimuth of the point(s) – pair of equations also specify straight line projection(s) from origin to the point(s)

Intersection of straight line project(s) with the camera image plane (which is oriented parallel to the YZ plane; and is 4 inches ahead of the focal point axes system origin):

$$X_D = +4$$

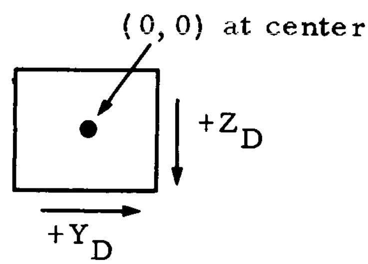
$$\tan \beta_C = \frac{Y_D}{X_D}$$

$$\tan \alpha_C = \frac{Z_D}{X_D}$$

Solution is for Y_D and Z_D

Result is two dimensional coordinates of point(s) in the camera plane, which is parallel with the $Y_D Z_D$ plane and whose plane equation is

$$X_D = +4$$



Solving for Y_D and Z_D in terms of X_A, Y_A, and Z_A:

$$X_C = \cos\epsilon \ \cos\gamma \ X_A + \sin\epsilon \ \cos\gamma \ Y_A - \sin\gamma \ (Z_A + 34)$$

$$Y_C = -\sin\epsilon \ X_A + \cos\epsilon \ Y_A$$

$$Z_C = \cos\epsilon \ \sin\gamma \ X_A + \sin\epsilon \ \sin\gamma \ Y_A + \cos\gamma \ (Z_A + 34)$$

For Case 1 and 2: $\epsilon = 0^{\circ}$, $\gamma = -5^{\circ}$

For Case 3: $\epsilon = 0^{\circ}$, $\gamma = -12.5^{\circ}$

Also:

$$X_D = 4$$

$$Y_D = \frac{X_D(Y_C)}{X_C} = 4\,(Y_C/X_C)$$

$$Z_D = \frac{X_D(Z_C)}{X_C} = 4\,(Z_C/X_C)$$

	Cases 1 and 2	Case 3
The bounds for β_C:	$\pm 14.5^\circ$	$\pm 26.5^\circ$
The bounds for α_C:	$\pm 11.5^\circ$	$\pm 21.45^\circ$

Therefore, the bounds are:

$Y_D = \pm 4\ (0.2585) = \pm 1.0340$ -- Cases 1 and 2

$Y_D = \pm 4\ (0.499) = \pm 1.996$ -- Case 3

$Z_D = \pm 4\ (0.204) = \pm 0.816$ -- Cases 1 and 2

$Z_D = \pm 4\ (0.393) = \pm 1.572$ -- Case 3

Once the overlay dimensions are specified, Y_D and Z_D would be scaled to fit those dimensions.

Generally:

$$Y_D = \frac{4Y_A}{(\cos\gamma^\circ)\,X_A + (\sin\gamma^\circ)\,Z_A + (34)\,(\sin\gamma^\circ)}$$

$$Z_D = 4\left(\frac{-(\sin\gamma^\circ)\,X_A + (\cos\gamma^\circ)\,Z_A + (34)\,(\cos\gamma^\circ)}{(\cos\gamma^\circ)\,X_A + (\sin\gamma^\circ)\,Z_A + (34)\,(\sin\gamma^\circ)}\right)$$

b. <u>Vehicle Dimensions (Reference: Figure 34)</u>

4" = D_1 = distance between camera azimuthal rotation axis and vidicon face

32" = D_2 = lateral distance (Y_A) between two front wheels (outside edges)

1-7/8" = D_3 = distance between centerline of center wheels and camera azimuthal rotation axis of vidicon

7-3/4"	$= D_4$	= height of forward bumper from a flat surface
27"	$= D_5$	= distance between left front wheel center and left middle wheel center (also between left middle wheel center and left rear diameter of each wheel)
18"	$= D_6$	= diameter of each wheel
2-1/2"	$= D_7$	= distance between forward bumper and front face of forward wheel
8"	$= D_8$	= wheel width
13-1/2"	$= D_9$	= width of forward bumper
13"	$= D_{10}$	= width of forward compartment, upon which the forward bumper is mounted
34"	$= D_{11}$	= height of camera axes coordinate system from flat surface

c. Inputs into Translation-Transformation System

1) Projected vehicle image

Let X_{10} = distance vehicle travels in 10 seconds

$$X_{10} = (10)(0.675 \frac{\text{miles}}{\text{hr}}) (\frac{5280 \times 12}{3600}) = 118.8 \text{ inches}$$

a) Coordinates of wheel surface contact lines:

Wheel→	Left Front	Right Front	Left Middle	Right Middle
X_A	$X_{10} + D_3 + D_5$	$X_{10} + D_3 + D_5$	$X_{10} + D_3$	$X_{10} + D_3$
Y_A	$\frac{-D_2}{2}$ to $(\frac{-D_2}{2} + D_8)$	$\frac{+D_2}{2}$ to $(\frac{+D_2}{2} - D_8)$	$\frac{-D_2}{2}$ to $(\frac{-D_2}{2} + D_8)$	$\frac{+D_2}{2}$ to $(\frac{+D_2}{2} - D_8)$
Z_A	0	0	0	0

or, substituting:

X_A	+147.7	+147.7	+120.7	+120.7
Y_A	-16 to -8 $\Delta = 1$	+16 to +8 $\Delta = 1$	-16 to -8 $\Delta = 1$	+16 to +8 $\Delta = 1$
Z_A	0	0	0	0

b) Coordinates of front wheel forward contact lines:

	Left Front	Right Front
X_A	$X_{10} + D_3 + D_5 + \frac{D_6}{2} = +156.7$	Same: +156.7
Y_A	As in a: -16 to -8 $\Delta = 1$	As in a: +16 to +8 $\Delta = 1$
Z_A	$\frac{-D_6}{2} = -9$	Same: -9

c) Coordinates of front bumper:

$X_A = X_{10} + D_3 + D_5 + \frac{D_6}{2} - D_7 = +154.2$

$Y_A = \frac{-D_9}{2}$ to $\frac{+D_9}{2} = -6.75$ to $+6.75$ $\Delta = 1$

$Z_A = -D_4 = -7.75$

2) Grid System

a) Radial lines:

$X_A = \alpha$ to N , $\Delta = 0.01$

$Y_A = (X_A - \alpha) \tan \beta + K$ $Z_A = 0$

where α = distance to line connecting forward contact line segments of front wheels in projected image:

$\alpha = +156.7$ $\Delta = 0.01$
N = large number
$\beta = \pm 10^\circ, \pm 20^\circ$
$K = 0$

b) Range lines:

$X = \alpha + R \sin \beta$ $\beta = 0^\circ$ to 180°, $\Delta 1^\circ$

$Y = K + R \cos \beta$ $Z_A = 0$

$\left.\begin{matrix}\alpha \\ K\end{matrix}\right|$ from 2. a above

$R = 120, 1200, 12000$

3) Crevasse hazard detection aid

Assume: I. Size of hazardous crevasse $\geq$ 0.7 M in diameter = 27.6"
II. Proper recognition of crevasse occurs when crevasse subtends a vertical FOV angle $\geq 1^\circ$

Using the dimensions of Figure 38:

$$\tan \beta = \frac{x}{34}$$

$$\tan (\beta + 1^\circ) = \frac{27.6 + x}{34} = \frac{\tan \beta + \tan (1^\circ)}{1 - (\tan \beta) \tan (1^\circ)}$$

$$\frac{27.6 + x}{34} = \frac{\frac{x}{34} + \tan (1^\circ)}{1 - (\frac{x}{34}) \tan (1^\circ)}$$

x = 215.7" = distance between camera axes system origin surface subpoint and near lip of crater 27.6" in diameter at which the crater subtends an angle of 1° from a camera mounted 34" above the surface

The crevasse hazard detection aid is composed of arcs of two concentric circles centered on the vidicon face surface subpoint and separated by a distance equal to the diameter of a "hazardous" crevasse = 27.6" in diameter:

$$X = \rho + R \sin \beta \qquad Z_A = 0$$

$$Y = K + R \cos \beta$$

$$R = \begin{cases} 215.7 + \frac{27.6}{2} = 229.5 \\ 215.7 - \frac{27.6}{2} = 201.9 \end{cases}$$

$$\rho = D_1 = 4$$

$$K = 0$$

4) Possible path (two front wheels)

Dashed-lines which are straight line projections from 2 front wheels in direction of travel starting at the to +10 second point:

$$X_A = (X_{10} + D_3 + D_5 + \frac{D_6}{2}) \text{ to } N = +156.7 \text{ to } N \text{ (large number)}$$

$$Y_A = \pm (\frac{D_2}{2} - \frac{D_8}{2}) = +12 \text{ and } -12$$

$$Z_A = 0$$

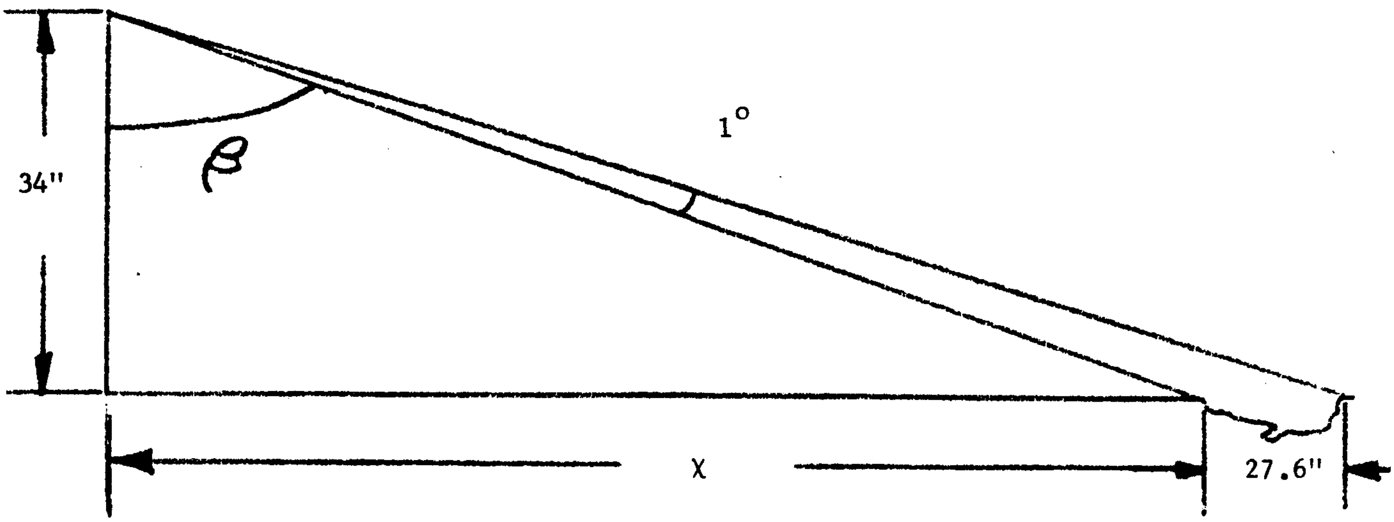


Figure 38. Geometric Relations Conforming to Assumptions Regarding Detection of Minimum Size Hazardous Crevasses From JPL Vehicle

3. Description of the Three Cases of Their Computer Programs

a. Basic Contents of Three Cases

The three cases are listed in Table.

b. Computer Programs Listings (FORTRAN IV Language for the Three Cases Applying to the JPL Vehicle

See Appendix G.

TABLE 5. GENERAL INFORMATION REGARDING THREE CASES RUN FOR JPL VEHICLE

Case	HFOV	VFOV	Centerline of VFOV is down from horizontal line-of-sight by the following angle: (centerline always in plane containing camera mast and parallel to direction of travel for non-turning vehicle)	Overlay includes the Following Display Aids				Arcs of Circles, Each Indicating Path Vehicle Follows when Commanded to a Fixed Heading Change as Follows (Case 3 only)	Crevasse Hazard Recognition Lines	Possible Path
				Vehicle Image Projected 10 Seconds into Picture		Grid System				
				Front and Middle Wheels Surface Contact Lines	Front Wheels Forward Contact and Front Bumper	Range Lines (Arc of Circles) at Following Ranges	Constant Heading Lines			
1	29°	23°	5°	Yes	Yes	10 feet 100 feet 1000 feet	10° left 20° left 10° right 20° right	DNA	Yes	Yes
2	29°	23°	5°	Yes	No	5 meters 10 meters 20 meters 30 meters 300 meters	Same as Case 1	DNA	No	Yes
3	53°	43°	12.5°	Yes	No	Same as Case 2	No	7.5° left, 7.5° right 15.0° left, 15.0° right 22.5° left, 22.5° right 30.0° left, 30.0° right Note: Points on these arcs are shown which are in seconds of travel.	No	Yes

IV. F TV Display System Equipment Interfacing with Remote Driving Aids Computer Program Output

1. Introduction

The remote guidance concept, as developed, requires the simultaneous display of the graphical computer 'X-Y' coordinate information derived from vehicle telemetry and command, and the display of the lurain data derived from the vehicle television camera. The lurain data would be represented as a video signal displayed on a television monitor, and, therefore, it is reasonable for the graphical information to also be represented as a video signal and be displayed on a television monitor. Although transparent plots could be generated and overlayed on the video display, the frequency of updating (approximately once per second) renders such a method impractical. Also, while the graphical data and the lurain data could be separately displayed and optically combined, the alignment of such equipment and the expense to transmit via the Jet Propulsion Laboratory monitor distribution network made this approach undesirable. The method considered most attractive was to convert the digital coordinate information to video, combine it with the lurain video, and display the composite result.

This section of the report describes the boundary conditions assumed, the equipment requirements developed from these assumptions, and shows a configuration of commercially available "off the shelf" units that will accomplish this task. In addition, the specifications of these selected units and their operating characteristics are given. Although alternative units are available in some cases, they could not be investigated in detail because of the time constraints of this study. It seemed most efficient to develop a single compatible configuration that could be demonstrated and investigated in greater detail, at a later date, than to present parameter tradeoff data for a range of possibly incompatible equipments.

2. Boundary Conditions

Since many of the key parameters such as the computer digital output signal and the lurain data video signal have not been precisely specified as to format, level and composition, certain assumptions had to be made. These assumptions were then structured as boundary conditions that would, wherever possible, allow the greatest flexibility as to equipment type and location.

The assumptions made were:

a) The maximum use should be made of equipment presently on site at Jet Propulsion Laboratory or under procurement consideration with regard to:

   (1) Computers
   (2) Monitors
   (3) Graphic display controllers
   (4) Video distribution network

b) The operation area would not necessarily be adjacent to the computer installation.

c) The equipment should be commercially available and "off the shelf" in order to minimize:

    (1) Cost
    (2) Development time
    (3) Procurement time
    (4) Installation time

d) The graphic resolution should be as high as practical.

e) The graphic display should be capable of being updated.

These basic assumptions were, after inquiry and investigation, structured into the following boundary conditions:

(1) The display signal should be EIA standard (replaces RTMA standard) 525 line, 30 frame per second video of 10 to 15mc bandwidth (in accordance with assumption a1, a4).

(2) The lurain data video signal will be available as EIA standard 525 line, 30 frame per second video of 10 to 15 mc bandwidth (derived from b and a4 as well as past release of lurain data to commercial TV and press).

(3) The computer will require a data set (in accordance with b).

(4) The computer is a Honeywell DDP124 or equivalent (in accordance with a1).

(5) The graphic display will be updated once per second (from previous operational requirements of Section II).

3. Equipment Requirements

The functional operation of the display group will be examined under the stated boundary conditions, and the individual equipment requirements will be developed. Inquiries made of equipment manufacturers and Jet Propulsion Laboratory operations personnel as well as equipment selection rationale will be discussed in this section.

A block diagram showing the functional operations of the display group is shown as Figure 39.

Since all computers require an input/output (I/O) controller in order to furnish data to peripheral equipments at the right time and in the right format, it seemed reasonable to require that the interface with the data set be common to most installations. If this were not the case, it would be necessary to develop a special I/O controller which would, in all probability,

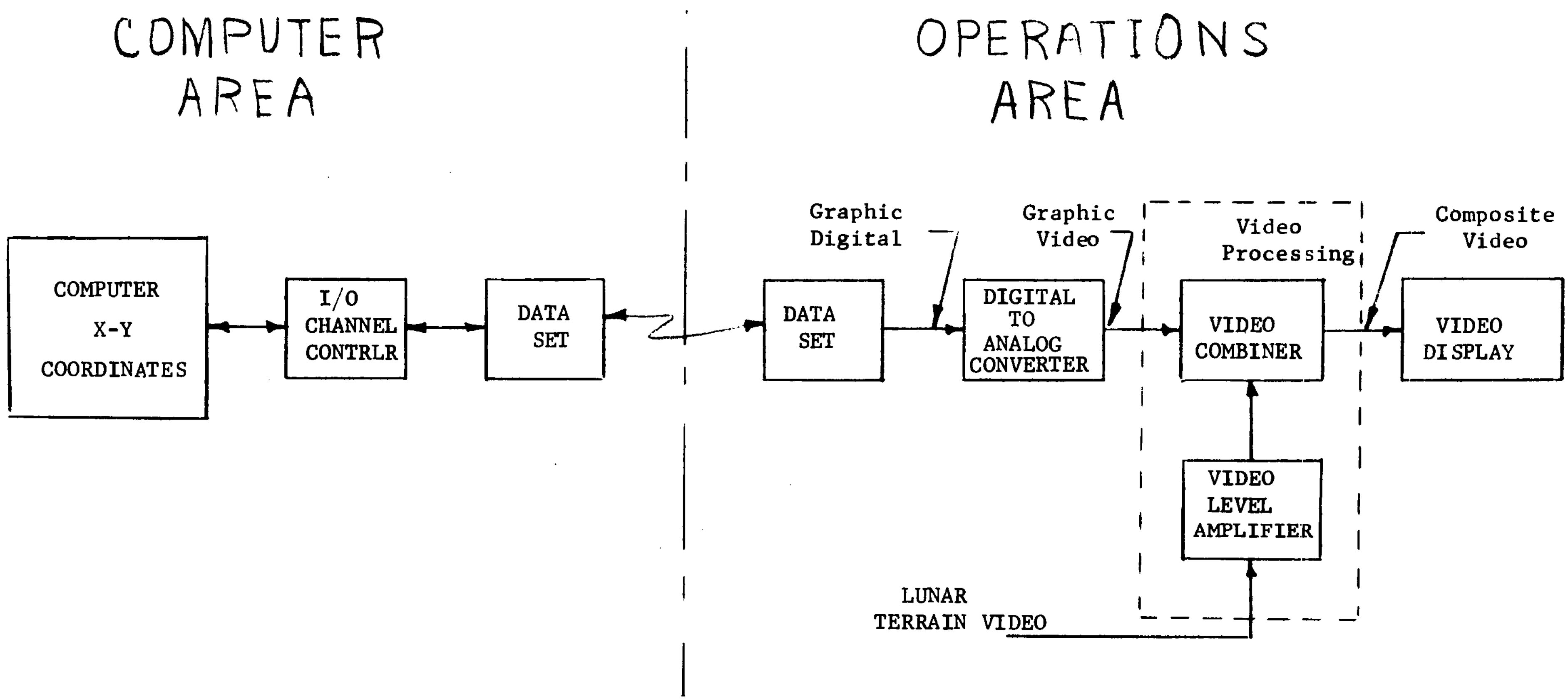


Figure 39. Display Group Functional Operations

be dependent on both the computer make and model type. Because both local and remote printers are used in almost all computer installations, the format selected was the standard ASCII code which is also compatible with all data sets. This code is a 10 bit start/stop code with 8 data bits per word, which has been used to operate both printers and alphanumeric character displays.

Three manufacturers of alphanumeric display equipments were contacted and technical data was requested. The three manufacturers were Applied Digital Data Systems, Inc. (Hauppauge, New York); Computer Communications, Inc. (Inglewood, California); and Canadian Westinghouse Company, Ltd. (Hamilton, Ontario). The Applied Digital Data Systems equipment did not have a graphical display capability which eliminated it as a possibility. The Computer Communications, Inc. equipment had an external synchronization feature and a 108 x 51 dot matrix in the graphical display mode. The Westinghouse equipment did not have an external synchronization capability and had a 50 x 63 dot matrix in the graphical display mode. The Computer Communications, Inc. (CCI) equipment was selected on a tentative basis, and after learning that Jet Propulsion Laboratory was considering the acquisition of the CCI CC-301 TV display controller for another application, it was selected as a baseline unit.

The function of the units shown within the dashed outline in Figure 39 is threefold: first, it adjusts the "sync tip" and "peak white" levels after amplification; second, it extracts a synchronizing signal to "drive" the digital to analog converter; and third, it combines the two video signals. Time was short, and a technical survey of these equipments was not conducted. It was established, however, that equipments were available from Ampex Corporation ($5000), Ball Brothers, Inc. (no quote), Central Dynamics, Inc. ($2000), and Grass Valley Group, Inc. ($1100). The Grass Valley Group equipment was selected because:

(1) It was compatible with the CC301.
(2) It was of modular construction.
(3) It was available for compatibility testing.
(4) It was priced competitively.
(5) The technical information was readily available from the local representative.

The specific units selected for the baseline were a GVG 940 video processing amplifier to adjust the video levels, A GVG 961 Synac to provide synchronization for the CC301 and a GVG 930 insert keyer to combine the video signals.

The video display unit had no particular requirements levied on it by the application and was considered to be a CONRAC CVA17.

The design and operation of the CC301 is such that it requires two ASCII characters (10 bits each) in order to extract 9 bits of graphical data, and since there are 5,508 bits (108 x 51) per frame, the data set must transmit 12,240 bits [(5508 x 20)/9] per frame. A graphical display update rate of once per second then results in the requirement that the data set be capable of handling 12,240 bits per second. If the signal is to be sent over a telephone line, a Bell System Model 301 data set would be required; the data set has a lease cost of $250 per month, and the telephone line has a lease cost of approximately $15 per month per mile. If the signal is not to be sent over a telephone line, an Astrocom Series 400 or equivalent would be required. The Series 400 operates at any speed, up to 96 kilobits/sec, for distances up to 3 miles with a 22 gauge twisted pair. The unit costs $2100, and its interface is identical to a data set. Since there seems to be a high probability that the operations area will be located reasonably close (within 3 miles) and could be handwired to the computer, the unit selected for the baseline was an Astrocom Series 400. The CC301 would in any case require a data set interface option to be included (option 1).

4. Baseline Configuration

A baseline configuration of the display group derived from equipments meeting the requirements of Section 3.0 is shown as Figure 40. Comparison to the functional operations block diagram of Section 3.0 indicates that:

(1) The data set function is performed by an Astrocom 400.

(2) The digital to analog conversion, providing the graphical information video, is performed by a CC301 with option 9 to permit external synchronization and with an option 1 to interface with the Astrocom 400 or a data set.

(3) The video processing is performed by three units:

(a) A GVG 940 that adjusts the "sync tip" and "peak white levels" of the lurain video prior to combining.

(b) A GVG 961 that synchronizes the graphical information video and the lurain video.

(c) A GVG 930 that combines the two video signals.

It should be noted that although the CC301 is electronically compatible with computer data this data must be in the correct format in order to be properly displayed. Either the remote driving aids computer program could be directly computed in the proper format or its output could be converted by an auxiliary program. Conversion programs, written in FORTRAN, have been prepared by Computer Communications, Inc. for both the IBM 360 and the IBM 1130 and could be prepared for any computer selected. Reference is made to the discussion on graph mode programming appearing at Page 6-49 of the CC30 Communications Station Reference Manual should direct computational formatting be desired.

5. Equipment Specifications

The general specifications for the equipments described in Section 4.0 are presented in this section. General characteristics are given since the detailed characteristics appear in the documents referenced in Appendix A.

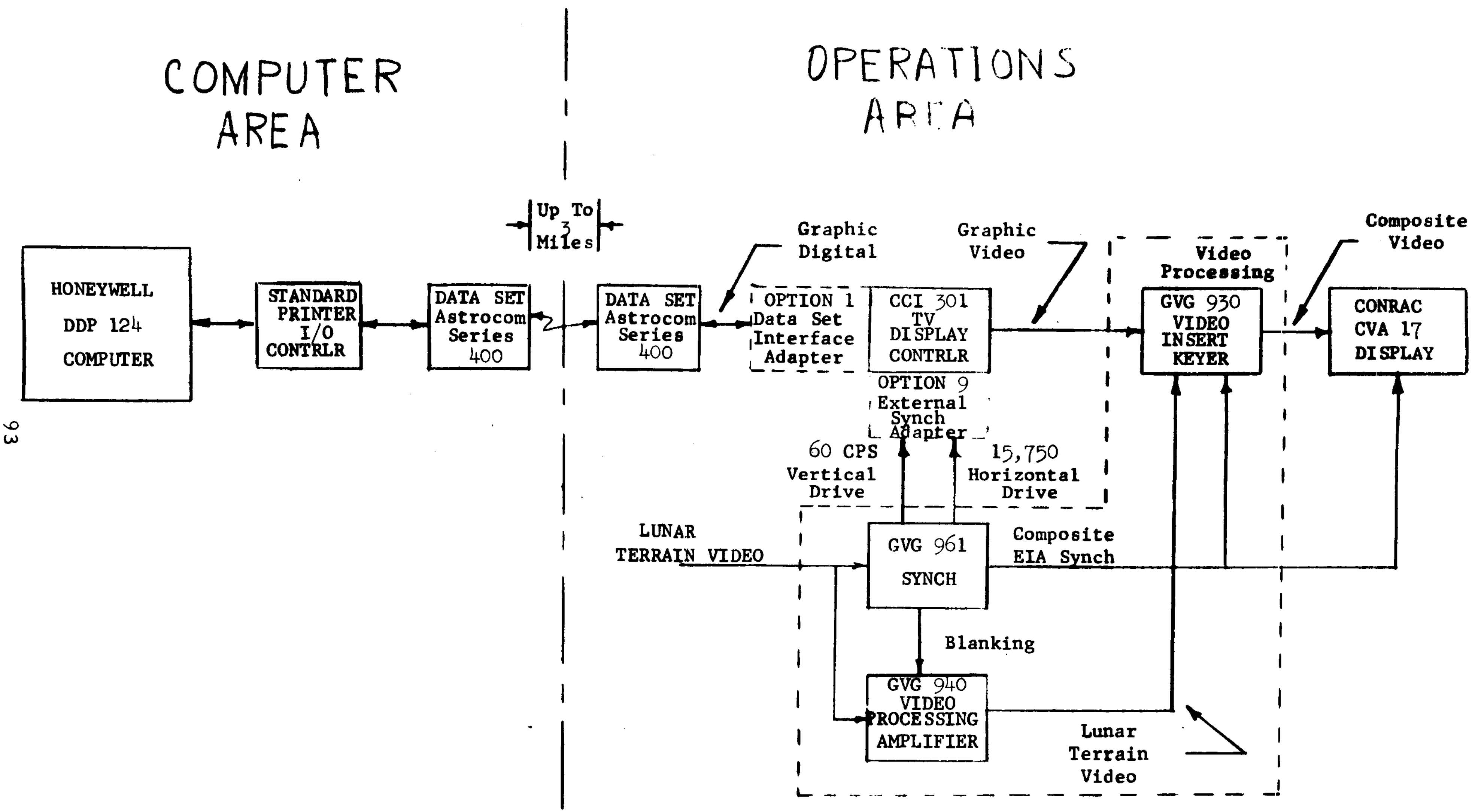


Figure 40. Baseline Configuration Diaplay Group

Astrocom Series 400

Input Wireline	Variable – 39 dBm to -19 dBm
Output Wireline	Choice of +7 dBm, 0 dBm, -7 dBm
Input Digital	Not available at this time
Output Digital	Not available at this time
Size	6 inches high x 12-3/4 inches wide x 13 inches deep
Price	$2100
Details	Appendix A, Item 6

CCI 301 – Options 1 and 9

Data Set	Bit Serial Asynchronous Start Stop ASCII
Input/Output	To 15 kilobits using RS-232B type interface with Astrocom Series 400
Synch Input	1-4 V P-P/75Ω Horizontal 1-4 V P-P/75Ω Vertical
Output	0-5 VTS/75Ω 100 NS Pulses
Power	360 watts 120 VAC 60 cps
Price	$7300
Details	Appendix A, Item 7

GVG Model 961 Synac

Input Composite Video	1 to 2 V P-P
Input Impedance	R > 25K, C < 15 PF
Outputs	Four; one each, processed sync, blanking, V Drive, H Drive. 75Ω source terminated 4 V P-P negative going. Rise time 75 NS. Overshoot and tilt < 1 per cent.
Power	+10 to +14 V TS DC unregulated at 120 ma -10 to -14 V TS DC unregulated at 150 ma
Size	3-1/4 inches high x 2-1/8 inches wide x 10 inches deep
Price	$680
Details	Appendix A, Item 8

GVG Model 940 Video Processing Amplifier

Input Composite Video	0.5 to 2.0 V P-P
Input Impedance	R > 50K, C < 15 PF
Output	4 at 1 V P-P/75Ω
Power	+10 to +14 V TS DC unregulated at 125 ma -10 to -14 V TS DC unregulated at 120 ma
Size	3-1/4 inches high x 2-1/8 inches wide x 10 inches deep
Price	$440
Details	Appendix A, Item 9

GVG Model 930 Video Insert Keyer

Input A	Noncomposite video 0.7 V P-P
Input B	Noncomposite video 0.7 V P-P
Synch	4 V P-P
Output	4 at 1 V P-P/75Ω
Power	+10 to +14 V TS DC unregulated at 100 ma -10 to -14 V TS DC unregulated at 110 ma
Size	3-1/4 inches high x 2-1/8 inches wide x 10 inches deep
Price	$440
Details	Appendix A, Item 10

GVG Model 900 Mounting Rack

Size	3-1/2 inches high x 19 inches wide x 11-1/2 inches deep
Price	$125
Details	None

GVG Model 900PS Power Supply

Power	120 V AC, 60 cps input 10-14 V DC positive and negative at 750 ma
Size	3-1/4 inches high x 2-1/8 inches wide x 10 inches deep
Price	$125
Details	None

CONRAC CVA 17

Input	Video 0. 25 to 0. 4 V P-P Video Synch 4 V P-P negative going 2 inputs: high impedance R = 470 K C = 15 PF los impedance 75
Response	100 MH ± 1 dB 800 line resolution 190 watts 120/240 V AC 60 cps
Size	17-3/8 inches high x 17-11/16 inches wide x 18 inches deep
Price	(Units assumed available at Jet Propulsion Laboratory)
Details	Appendix A, Item 11

APPENDIX A. REFERENCES

1. LRV Navigation and Guidance System Phase A Study Report, Jet Propulsion Laboratory Document 760-42, by G. K. Hornbrook et al, October 15, 1969.

2. Operations Profiles for Lunar Roving Missions, Jet Propulsion Laboratory Document 760-46 by C. W. McCormick et al, May 1970.

3. Human Engineering Guide to Equipment Design, Morgan et al, McGraw-Hill, 1963, New York.

4. Mechanical Vibrations, Tse et al. Allyn & Bacon, Inc., 1963.

5. Dual Mode Manned/Automated Lunar Roving Vehicle-Design Definition Study, Bendix Aerospace Systems Division, BSR-2815, January 1970.

6. Astroset 400 Series Data Communications Systems Product Data Flyer. Astrocom Corporation, 293 Commercial Street, St. Paul, Minnesota. Representative: The Thorson Company, 6824 Melrose Avenue, Los Angeles, California.

7. CC-30 Communications Station Reference Manual, and External Sync Option Description. 1 June 1969. Computer Communications, Inc., 701 West Manchester Boulevard, Inglewood, California.

8. Model 961 SYNAC Operating Instructions, December 1969. The Grass Valley Group, Inc., Post Office Box 1114, Grass Valley, California.

9. Model 940 Video Processing Amplifier, January 1970. The Grass Valley Group, Inc., Post Office Box 1114, Grass Valley, California.

10. Model 930/931 Insert Keyer Operating Instructions. September 1969. The Grass Valley Group, Inc., Post Office Box 1114, Grass Valley, California.

11. CONRAC Industrial Television Equipment Flyer. CONRAC Corporation, 600 N. Rimsdale Ave., Covina, California. CONRAC Division: Metrovonics, Inc., 3808 Catalina St., Los Alamitos, California.

APPENDIX B

Computer Program Listing and Results: Picture Smear (as a Percent Shift of a Scene Element) versus Vertical and Horizontal Pointing Angles

```
EXPØ       16:48    WED.    06/24/70

100 LET H=1
110 LET V=((H)*(1E3))/(3.6E3)
120 LET T=1E-2
130 LET P=0.10
140 LET J=2
150 DEF FNK(Y)=(Y*3.14159265/180)
160 PRINT"VELØCITY=";H;"KM/HR","EXPØSURE TIME=";T;"SEC."
170PRINT
180 PRINT"PICTURE ELEMENT SIZE=";P;"DEGREES ØF ARC"
190 PRINT
200 PRINT"DEG. DWN.","DEG. LATERAL","PERCENT","PERCENT","DISTANCE-"
210PRINT"FRØM HØRIZ.","FRØM VERTICAL","LATERAL","VERTICAL","CAMERA AXES"
220PRINT"LINE-ØF","CENTERLINE","SHIFT","SHIFT","ØRIGIN TØ"
230PRINT"SIGHT","ØF FØV"," "," ","SURFACE IN"
240PRINT" "," "," "," ","PERP. PLANE;"
250PRINT" "," "," "," ","ALSØ:"
260PRINT" "," "," "," ","(SURFACE DISTANCE FRØM CAMERA"
270PRINT" "," "," "," "," ØRIGIN SURFACE  SUBPØINT)"
280 PRINT
290 PRINT" "," "," "," ","(METERS)"
300 PRINT
310 FØR A=1 TØ 60
320 LET D=FNK(A)
330 LET C=J/(SIN(D))
340 LET N=V*T*(TAN(D))
350 DEF FNL(W)=(N*TAN(W))/(J*(((TAN(W))^2)+1)-N)
360 LET S2=ATN(FNL(D))
370 LET R=(S2)/(P*(FNK(1)))
380 PRINT A,"DNA"," ",(100)*R,C
390 LET S3=2/(TAN(D))
400 PRINT A," "," "," ",S3
410 FØR B=0 TØ 30, STEP 5
420 LET E=FNK(B)
430 LET S1=ATN(FNL(E))
440 LETL=(S1)/(P*(FNK(1)))
450 IF ((INT(A/4))-(A/4))<>0 THEN 470
460 PRINT A,B,(100)*L
470 NEXT B
480 NEXT A
490 END
```

EXPC 15:58 WED. 06/24/70

VELØCITY= 1 KM/HR EXPØSURE TIME= .01 SEC.

PICTURE ELEMENT SIZE= .1 DEGREES ØF ARC

DEG. DWN. FRØM HØRIZ. LINE-ØF SIGHT	DEG. LATERAL FRØM VERTICAL CENTERLINE ØF FØV	PERCENT LATERAL SHIFT	PERCENT VERTICAL SHIFT	DISTANCE-CAMERA AXES ØRIGIN TØ SURFACE IN PERP. PLANE ALSØ: [SURFACE DISTANCE FRØM CAMERA ØRIGIN SURFACE SUBPØINT] [METERS]
1	DNA		2.42388E-02	114.597
1				114.58
2	DNA		.096928	57.3074
2				57.2725
3	DNA		.217983	38.2146
3				38.1623
4	DNA		.387259	28.6712
4				28.6013
4	0	0		
4	5	.483188		
4	10	.951692		
4	15	1.39128		
4	20	1.78858		
4	25	2.13154		
4	30	2.40972		
5	DNA		.604553	22.9474
5				22.8601
6	DNA		.869605	19.1335
6				19.0287
7	DNA		1.18209	16.411
7				16.2887
8	DNA		1.54164	14.3706
8				14.2307
8	0	0		
8	5	.971219		
8	10	1.91292		
8	15	2.79648		
8	20	3.59505		
8	25	4.28436		
8	30	4.84347		
9	DNA		1.94782	12.7849
9				12.6275
10	DNA		2.40012	11.5175
10				11.3426
11	DNA		2.89802	10.4817
11				10.2891
12	DNA		3.44089	9.61947
12				9.40926

DEG. DWN. FRØM HØRIZ. LINE-ØF SIGHT	DEG. LATERAL FRØM VERTICAL CENTERLINE ØF FØV	PERCENT LATERAL SHIFT	PERCENT VERTICAL SHIFT	DISTANCE-CAMERA AXES ØRIGIN TØ SURFACE IN PERP. PLANE ALSØ: [SURFACE DISTANCE FRØM CAMERA ØRIGIN SURFACE SUBPØINT] [METERS]
12	0	0		
12	5	1.46903		
12	10	2.89341		
12	15	4.22984		
12	20	5.4377		
12	25	6.48028		
12	30	7.32591		
13	DNA		4.02808	8.89082
13				8.66295
14	DNA		4.65889	8.26713
14				8.02156
15	DNA		5.33253	7.72741
15				7.4641
16	DNA		6.0482	7.25591
16				6.97483
16	0	0		
16	5	1.98198		
16	10	3.9037		
16	15	5.70674		
16	20	7.3363		
16	25	8.74284		
16	30	9.88364		
17	DNA		6.80502	6.84061
17				6.54171
18	DNA		7.60208	6.47214
18				6.15537
19	DNA		8.43839	6.14311
19				5.80842
20	DNA		9.31295	5.84761
20				5.49495
20	0	0		
20	5	2.51602		
20	10	4.95554		
20	15	7.24437		
20	20	9.31295		
20	25	11.0984		
20	30	12.5465		
21	DNA		10.2247	5.58086
21				5.21018
22	DNA		11.1725	5.33893
22				4.95017
23	DNA		12.1552	5.11861
23				4.7117
24	DNA		13.1717	4.91719
24				4.49207

DEG. DWN. FRØM HØRIZ. LINE-ØF SIGHT	DEG. LATERAL FRØM VERTICAL CENTERLINE ØF FØV	PERCENT LATERAL SHIFT	PERCENT VERTICAL SHIFT	DISTANCE-CAMERA AXES ØRIGIN TØ SURFACE IN PERP. PLANE, ALSØ: [SURFACE DISTANCE FRØM CAMERA ØRIGIN SURFACE SUBPØINT] [METERS]
24	0	0		
24	5	3.07808		
24	10	6.06255		
24	15	8.86266		
24	20	11.3933		
24	25	13.5774		
24	30	15.3488		
25	DNA		14.2206	4.7324
25				4.28901
26	DNA		15.3007	4.56234
26				4.10061
27	DNA		16.4107	4.40538
27				3.92522
28	DNA		17.5493	4.26011
28				3.76145
28	0	0		
28	5	3.6764		
28	10	7.24098		
28	15	10.5853		
28	20	13.6077		
28	25	16.2163		
28	30	18.3318		
29	DNA		18.7149	4.12533
29				3.6081
30	DNA		19.9063	4
30				3.4641
31	DNA		21.122	3.88321
31				3.32856
32	DNA		22.3605	3.77416
32				3.20067
32	0	0		
32	5	4.32109		
32	10	8.51073		
32	15	12.4415		
32	20	15.9937		
32	25	19.0596		
32	30	21.5458		
33	DNA		23.6202	3.67216
33				3.07973
34	DNA		24.8996	3.57658
34				2.96512
35	DNA		26.1973	3.48689
35				2.8563
36	DNA		27.5115	3.4026
36				2.75276

DEG. DWN. FRØM HØRIZ. LINE-ØF SIGHT	DEG. LATERAL FRØM VERTICAL CENTERLINE ØF FØV	PERCENT LATERAL SHIFT	PERCENT VERTICAL SHIFT	DISTANCE-CAMERA AXES ØRIGIN TØ SURFACE IN PERP. PLANE ALSØ: [SURFACE DISTANCE FRØM CAMERA ØRIGIN SURFACE SUBPØINT] [METERS]
36	0	0		
36	5	5.02489		
36	10	9.89688		
36	15	14.4677		
36	20	18.5984		
36	25	22.1633		
36	30	25.0542		
37	DNA		28.8407	3.32328
37				2.65409
38	DNA		30.1833	3.24854
38				2.55988
39	DNA		31.5376	3.17803
39				2.46979
40	DNA		32.902	3.11145
40				2.38351
40	0	0		
40	5	5.80425		
40	10	11.4318		
40	15	16.7115		
40	20	21.4827		
40	25	25.6002		
40	30	28.939		
41	DNA		34.2748	3.04851
41				2.30074
42	DNA		35.6543	2.98895
42				2.22123
43	DNA		37.0389	2.93256
43				2.14474
44	DNA		38.4268	2.87911
44				2.07106
44	0	0		
44	5	6.68107		
44	10	13.1587		
44	15	19.2358		
44	20	24.7275		
44	25	29.4666		
44	30	33.3093		
45	DNA		39.8164	2.82843
45				2.
46	DNA		41.2059	2.78033
46				1.93138
47	DNA		42.5938	2.73465
47				1.86503
48	DNA		43.9782	2.69127
48				1.80081

DEG. DWN. FRØM HØRIZ. LINE-ØF SIGHT	DEG. LATERAL FRØM VERTICAL CENTERLINE ØF FØV	PERCENT LATERAL SHIFT	PERCENT VERTICAL SHIFT	DISTANCE-CAMERA AXES ØRIGIN TØ SURFACE IN PERP. PLANE ALSØ: [SURFACE DISTANCE FRØM CAMERA ØRIGIN SURFACE SUBPØINT] [METERS]
48	0	0		
48	5	7.68525		
48	10	15.1365		
48	15	22.1268		
48	20	28.4434		
48	25	33.8943		
48	30	38.3139		
49	DNA		45.3574	2.65003
49				1.73857
50	DNA		46.7299	2.61081
50				1.6782
51	DNA		48.0939	2.57352
51				1.61957
52	DNA		49.4478	2.53804
52				1.56257
52	0	0		
52	5	8.85905		
52	10	17.4482		
52	15	25.5059		
52	20	32.7869		
52	25	39.0696		
52	30	44.1632		
53	DNA		50.7899	2.50427
53				1.50711
54	DNA		52.1186	2.47214
54				1.45309
55	DNA		53.4322	2.44155
55				1.40042
56	DNA		54.7291	2.41244
56				1.34902
56	0	0		
56	5	10.2643		
56	10	20.2159		
56	15	29.5514		
56	20	37.9866		
56	25	45.2649		
56	30	51.1652		
57	DNA		56.0078	2.38473
57				1.29882
58	DNA		57.2667	2.35836
58				1.24974
59	DNA		58.5043	2.33327
59				1.20172
60	DNA		59.719	2.3094
60				1.1547

DEG. DWN. FRØM HORIZ. LINE-ØF SIGHT	DEG. LATERAL FRØM VERTICAL CENTERLINE ØF FØV	PERCENT LATERAL SHIFT	PERCENT VERTICAL SHIFT	DISTANCE-CAMERA AXES ØRIGIN TØ SURFACE IN PERP. PLANE ALSØ: [SURFACE DISTANCE FRØM CAMERA ØRIGIN SURFACE SUBPØINT] [METERS]
60	0	0		
60	5	11.9958		
60	10	23.6258		
60	15	34.5356		
60	20	44.3927		
60	25	52.8973		
60	30	59.791		

TIME: 23 SECS.

APPENDIX C. PRELIMINARY COMPUTERIZED EVALUATION OF ON-BOARD CIRCUITRY INTENDED FOR MINIMIZATION OF SCENE JITTER

(Reference Figure 5 of IIA. 2. h)

A computer evaluation was made of the previously described circuitry wherein the output parameters were set to:

1) Comparison Circuit: Output for pitch error $\leq 5^{\circ}$

$J\text{-}E = 5^{\circ}, \; E = 0.01^{\circ}, \; J = 5.1^{\circ}$

2) Rate Gate: Output for error rate $\leq 1^{\circ}/\text{sec}$

$(E^{\circ}/Tex = 0.01^{\circ}/0.01 \text{ sec} = 1^{\circ}/\text{sec})$

3) Acceleration Gate: Output for acceleration $\leq 200^{\circ}/\text{sec}$

$(E^{\circ}/(Tex)^2/2 = 0.01^{\circ}/_{(0.01)^2/2} = 200^{\circ}\text{sec})$

As mentioned previously, the damped free vibration frequency response will be a collection of damped sinusoids for a multi-degree of freedom device such as a 4-wheel vehicle.

We shall simplify the response to a single dominant term of the form:

$$Ae^{-DW_n t} \sin(W_d t)$$

where

$$D = \frac{C}{\sqrt{2\,KM}} = \text{damping factor}$$

$$W_n = 2\pi f_n = \sqrt{\frac{K}{M}}$$ where f_n = natural frequency of oscillation

$$W_n = \left(\sqrt{1 - D^2}\right)(W_n) = 2\pi f_D$$ where f_D = actual frequency of damped free oscillation

K = equivalent spring constant

C = equivalent damping coefficient

M = mass supported by system

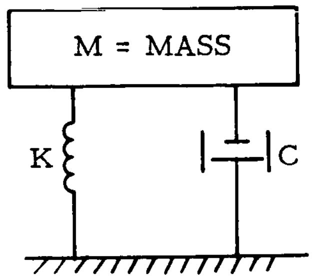


Figure C-1. Damped Free Vibration

A mechanical system designed to minimize the motion due to vibration would establish a value of $D \cong 0.7$. However, we will evaluate the system for a range of $0.5 \leq D \leq 0.9$ for a frequency range 0.25 cps $\leq f_n \leq 20$ cps and for values of $2^\circ \leq A \leq 10^\circ$.

The computer program used is listed in Table C-1 and its output immediately follows.

Values of T_s (reference Figure 6 of IIA.2.h) in seconds are plotted versus f_n in cps for fixed values of D and A (see Figures C-2, C-3, and C-4).

It is seen from Figures C-2, C-3, and C-4 that T_s is < 1.0 second for f_n greater than 0.15 cps for ($A = 10^\circ$, $D = 0.5$) and ($A = 10^\circ$, $D = 0.7$). Also $T_s < 1.0$ second for f_n greater than 0.1 cps for ($A = 10^\circ$, $D = 0.9$).

The pitch average box in Figure 5 of II A.2.h can be designed to nullify the effect of the low f_n components ($f_n \leq 0.15$ cps) of the multi-term transient response. The significant term of high f_n ($f_n > 0.15$ cps) components (or harmonics of the fundamental f_n) will generate time delays (T_s) in picture taking on the order of 0.5 seconds or less.

Thus, assuming a slow velocity (1/2 KM/hr $\cong$ 1/8 meter/sec) through rough lurain and perturbations spaced >2 seconds of travel (= 1/4 meter) apart, the on-board circuitry will permit a picture to be transmitted at least once every two seconds, at an optimum time from the criteria of near-minimum scene jitter and near-minimum smear.

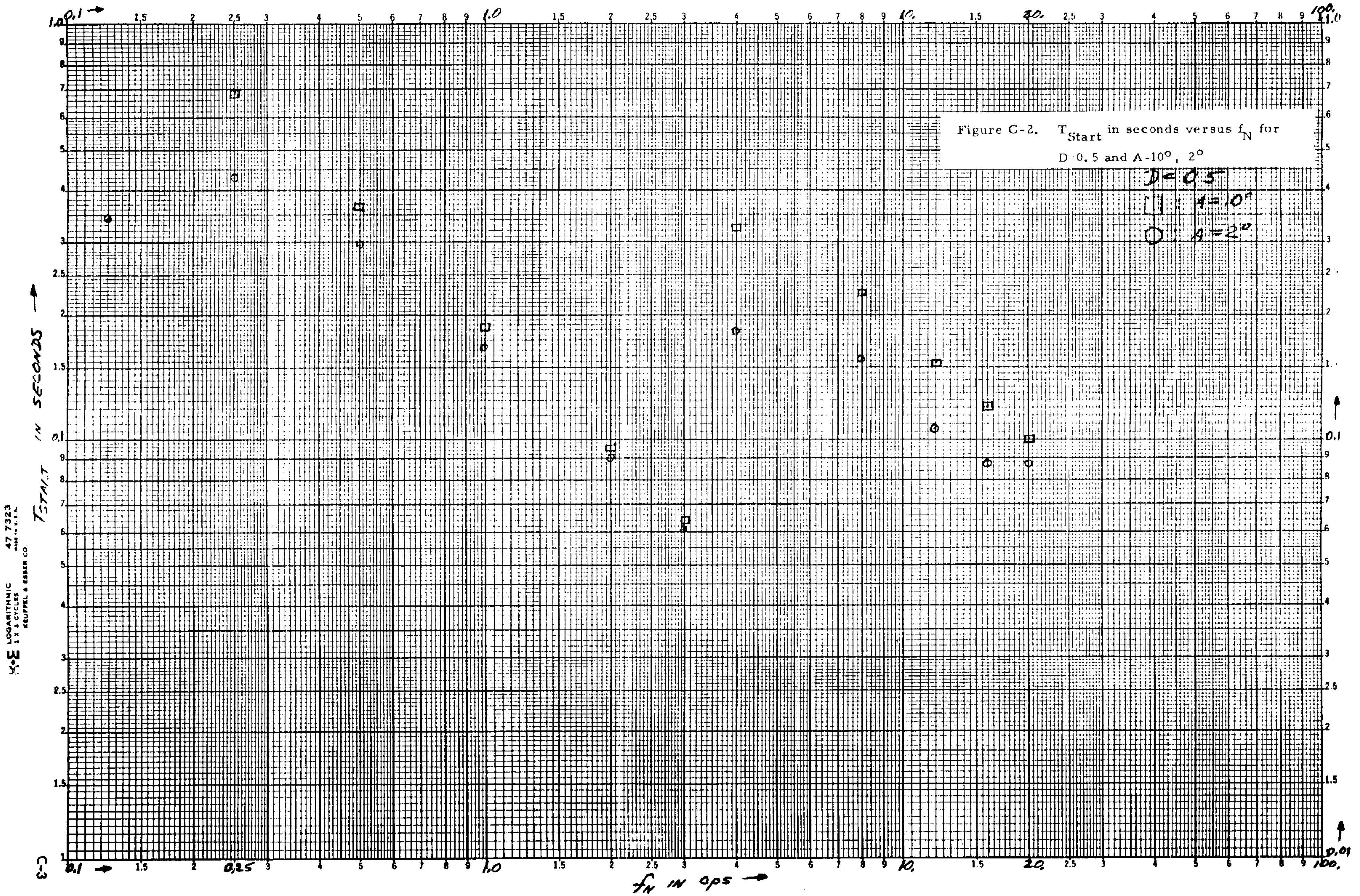


Figure C-2. T_{Start} in seconds versus f_N for D=0.5 and A=10°, 2°

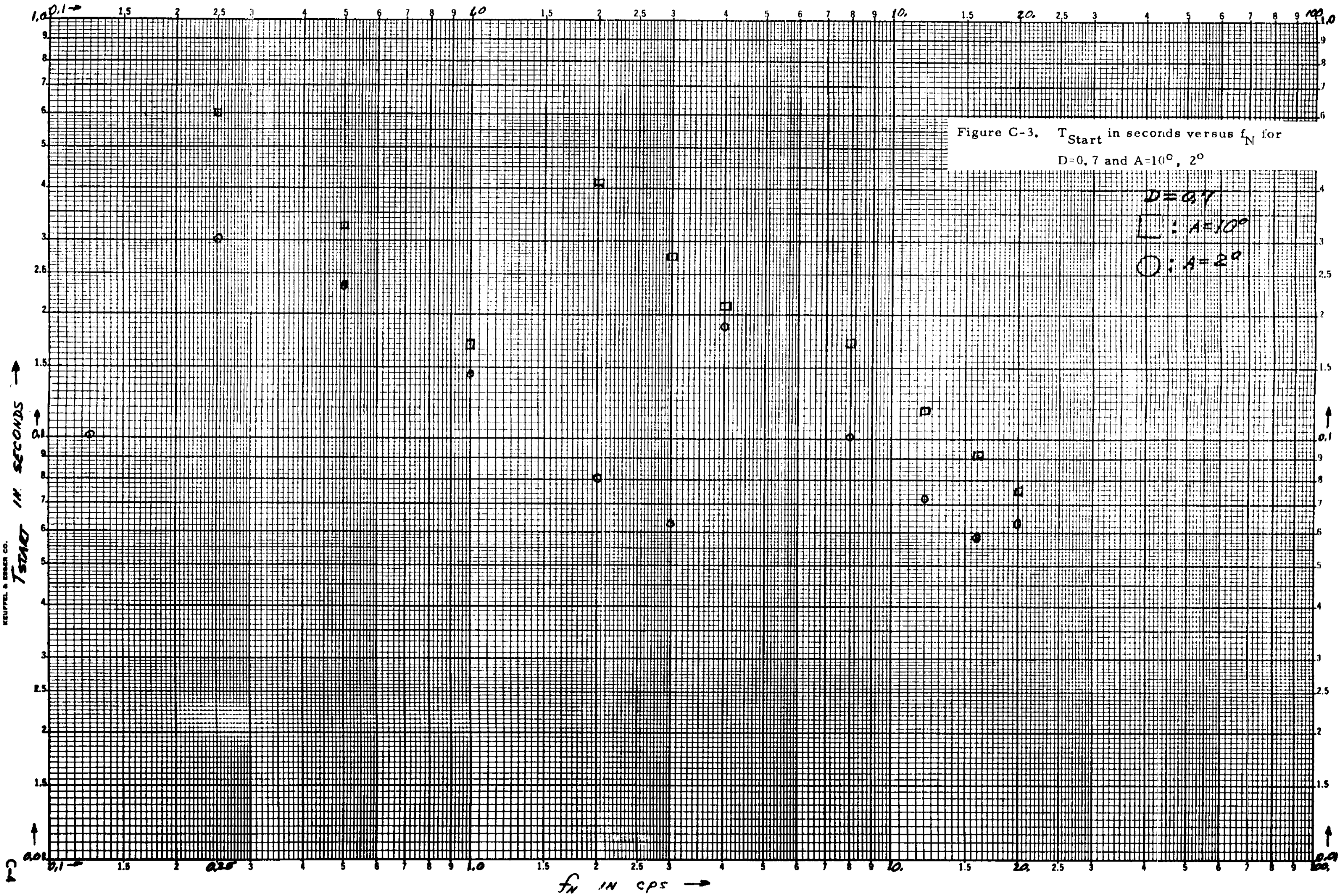


Figure C-3. T_{Start} in seconds versus f_N for $D=0.7$ and $A=10^\circ$, 2°

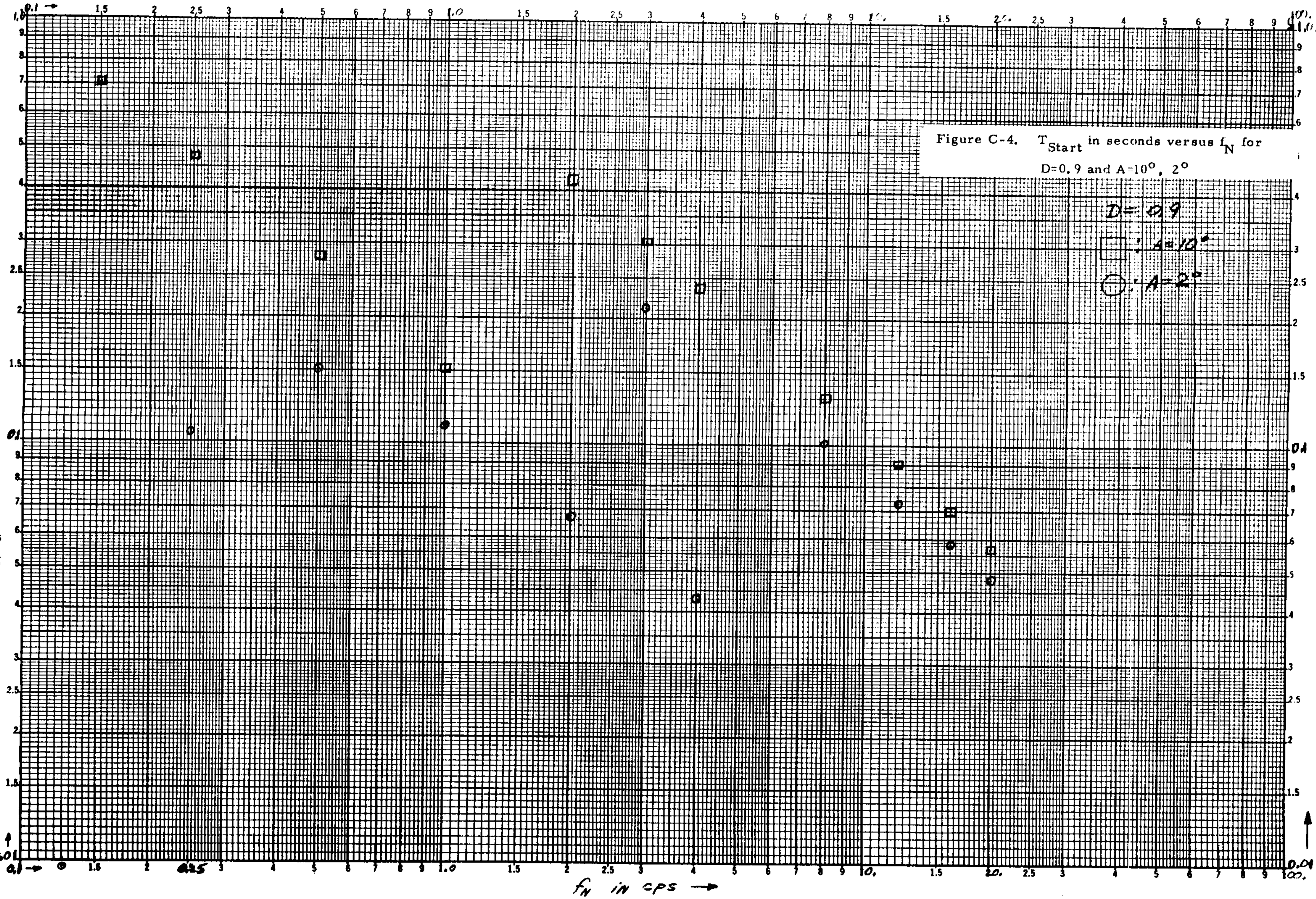


Figure C-4. T_{Start} in seconds versus f_N for D=0.9 and A=10°, 2°

TABLE I. EXP02 COMPUTER PGM

```
LISTNH
100 E1=2.71828183
110 P=3.14159265
120 PRINT"ERRØR","ERRØR","ERRØR","ERRØR RATE","ERRØR ACCEL."
130 PRINT"AT TS","AT TN","AT TS+10 MS.","AT TS"
140 PRINT"(DEG.)","(DEG.)","(DEG.)","(DEG./SEC.)","DEG/SEC/SEC"
150 PRINT
160 FØR I=4 TØ 8,STEP 4
170 F1=I/4
180 W1=(F1)*2*P
190 FØR B=5 TØ 9,STEP 2
200 D=B/10
210 F2=(1-(D↑2))↑(0.5)
220 W2=(F2)*(W1)
230 FØR A=2 TØ 10,STEP 2
240 H=0
250 FØR J=1 TØ 2000
260 T=J/2000
270 DEF FNC(T)=A*((E1)↑((-D)*(W1)*T))
280 DEF FND(T)=SIN((W2)*T)
290 DEF FNE(T)=(FNC(T))*(FND(T))
300 IF (ABS(FNE(T)))>5 THEN 450
310 DEF FNP(T)=CØS((W2)*T)
320 DEF FNR(T)=(FNC(T))*(((-D)*(W1)*(FND(T)))+((W2)*(FNP(T))))
330 IF(ABS(FNR(T)))>1 THEN 450
340 DEF FNU(T)=(FND(T))*(((D↑2)*((W1)↑2))-((W2)↑2))
350 DEF FNV(T)=(FNP(T))*(-2)*D*(W1)*(W2)
360 DEF FNA(T)=(FNC(T))*((FNU(T))-(FNV(T)))
370 IF (ABS(FNA(T)))>200 THEN 450
380 H=H+1
390 IF H>1 THEN 460
400 E2=A*((E1)↑((-D)*(W1)*((ATN((F2)/D))/(W2))))*(F2)
410 T2=(ATN((F2)/D))/(W2)
420PRINT"-----------------------------------------------------"
430PRINTF1;"CPS";" D=";D;" PEAK=";A;"DEG";" TS=";T;"SEC";" TN=";T2;"SEC"
440 PRINT FNE(T),(E2),FNE(T+0.01),FNR(T),FNA(T)
450 NEXT J
460 NEXT A
470 NEXT B
480 NEXT I
490 END
```

TABLE I. (Continued)

EXP02 9:44 TUES. 06/02/70

ERRØR AT TS [DEG.]	ERRØR AT TN [DEG.]	ERRØR AT TS+10 MS. [DEG.]	ERRØR RATE AT TS [DEG./SEC.]	ERRØR ACCEL. DEG/SEC/S
.125 CPS D= .5 PEAK= 2 DEG TS= .3415 SEC TN= 1.5396 SEC				
.402612	.946207	.412556	.999567	.785058
.125 CPS D= .5 PEAK= 4 DEG TS= .86 SEC TN= 1.5396 SEC				
1.57562	1.89241	1.58553	.999484	.784993
.125 CPS D= .7 PEAK= 2 DEG TS= .102 SEC TN= 1.41811 SEC				
.108122	.654966	.118058	.99942	1.16295
.125 CPS D= .7 PEAK= 4 DEG TS= .6005 SEC TN= 1.41811 SEC				
.950225	1.30993	.960138	.999682	1.66191
.125 CPS D= .7 PEAK= 6 DEG TS= .815 SEC TN= 1.41811 SEC				
1.69183	1.9649	1.70172	.999089	2.10042
.125 CPS D= .7 PEAK= 8 DEG TS= .9375 SEC TN= 1.41811 SEC				
2.39824	2.61986	2.4081	.999384	2.51906
.125 CPS D= .9 PEAK= 2 DEG TS= .0005 SEC TN= 1.31745 SEC				
3.48226E-04	.343533	7.13611E-03	.68421	.967753
.125 CPS D= .9 PEAK= 4 DEG TS= .212 SEC TN= 1.31745 SEC				
.24969	.687066	.259604	.999217	1.75762
.125 CPS D= .9 PEAK= 6 DEG TS= .452 SEC TN= 1.31745 SEC				
.671838	1.0306	.681743	.999591	2.34145
.125 CPS D= .9 PEAK= 8 DEG TS= .6 SEC TN= 1.31745 SEC				
1.06772	1.37413	1.07762	.999711	2.88863
.125 CPS D= .9 PEAK= 10 DEG TS= .7025 SEC TN= 1.31745 SEC				
1.44964	1.71766	1.45952	.998918	3.41523

TABLE I. (Continued)

ØXPØ2 17:25 WED. 05/06/70

^ERRØR @P TS [DEG.]	ERRØR AT TN [DEG.]	ERRØR AT TS+10 MS. [DEG.]	ERRØR RATE AT TS [DEG./SEC.]	ERRØR ACCEL. AT TS EG/SEC/SEC
.25 CPS	D= .5	PEAK= 2 DEG	TS= .43 SEC	TN= .7698 SEC
.787812	.946207	.797632	.999484	-3.51384
.25 CPS	D= .5	PEAK= 4 DEG	TS= .583 SEC	TN= .7698 SEC
1.80302	1.89241	1.81271	.999232	-6.01835
.25 CPS	D= .5	PEAK= 6 DEG	TS= .641 SEC	TN= .7698 SEC
2.77662	2.83862	2.78613	.993054	-8.41091
.25 CPS	D= .5	PEAK= 8 DEG	TS= .671 SEC	TN= .7698 SEC
3.73689	3.78483	3.7463	.994115	-10.782
.25 CPS	D= .5	PEAK= 10 DEG	TS= .69 SEC	TN,.7698 SEC
4.69232	4.73104	4.70156	.989845	-13.1327
.25 CPS	D- .7	PEAK= 2 DEG	TS= .301 SEC	TN< .709055 SEC
.475861	.654966	.485665	.997156	-3.367
.25 CPS	D= .7	PEAK= 4 DEG	TS= .469 SEC	TN= .709055 SEC
1.19937	1.30993	1.20909	.998095	-5.15425
.25 CPS	D= .7	PEAK= 6 DEG	TS= .538 SEC	TN= .709055 SEC
1.88467	1.9649	1.89428	.994791	-6.83789
.25 CPS	D= .7	PDAK= 8 DEG	TS= .576 SEC	TN= .709055 SEC
2.55686	2.61986	2.56636	.991915	-8.49014
.25 CPS	D= .7	PEAK= 10 DEG	TS= .6 SEC	TN= .709055 SEC
3.22283	3.274[illegible]3	3.23223	.990987	-10.1313
.25 CPS	D= .	PEAK= 2 DEG	TS= .106 SEC	TN= .658727 SEC
.124845	.34[illegible][illegible]33	.134681	.999217	-3.13326
.25 CPS	D= .9	PEAK= 4 DEG	TS= .3 SEC	TN= .658727 SEC
.533862	.[illegible]87066	.543653	.999711	-4.14387
.25 CPS	D= .9	PEAK= 6 DEG	TS= .389 SEC	TN- .658727 SEC
.911206	1.0306	.92094	.99859	-5.07176
.25 CPS	D= .9	PEAK= 8 DEG	TS= .442 SEC	TN= .658727 SEC
1.27639	1.37413	1.28604	.994605	-5.96156
.25 CPS	D= .9	PEAK= 10 DEG	TS= .477 SEC	TN= .658727 SEC
1.63457	1.71766	1.64416	.993235	-6.84144

TABLE I. (Continued)

```
--------------------------------------------------------------------
 .5   CPS D= .5    PEAK= 2 DEG TS= .2915   SEC TN= .3849   SEC
 .901508        .946207        .910903        .999232        3.13918
--------------------------------------------------------------------
 .5   CPS D= .5    PEAK= 4 DEG TS= .3355   SEC TN= .3849   SEC
 1.86845        1.89241        1.87732        .994115        3.1231
--------------------------------------------------------------------
 .5   CPS D= .5    PEAK= 6 DEG TS= .3515   SEC TN= .3849   SEC
 2.82245        2.83862        2.83076        .98479         3.09381
--------------------------------------------------------------------
 .5   CPS D= .5    PEAK= 8 DEG TS= .3595   SEC TN= .3849   SEC
 3.77246        3.78483        3.78033        .986654        3.09966
--------------------------------------------------------------------
 .5   CPS D= .5    PEAK= 10  DEG TS= .3645   SEC TN= .3849   SEC
 4.72111        4.73104        4.72848        .983069        3.0884
--------------------------------------------------------------------

 .5   CPS D= .7    PEAK= 2 DEG TS= .2345   SEC TN= .354528 SEC
 .599684        .654966        .609155        .998095        10.0717
--------------------------------------------------------------------
 .5   CPS D= .7    PEAK= 4 DEG TS= .288 SEC TN= .354528 SEC
 1.27843        1.30993        1.28751        .991915        16.4756
--------------------------------------------------------------------
 .5   CPS D= .7    PEAK= 6 DEG TS= .308 SEC TN= .354528 SEC
 1.94244        1.9649         1.95125        .997695        22.7924
--------------------------------------------------------------------
 .5   CPS D= .7    PEAK= 8 DEG TS= .319 SEC TN= .354528 SEC
 2.60268        2.61986        2.61112        .992236        29.024
--------------------------------------------------------------------
 .5   CPS D= .7    PEAK= 10   DEG TS= .3255   SEC TN= .354528 SEC
 3.26062        3.27483        3.26881        .999344        35.2892
--------------------------------------------------------------------
 .5   CPS D= .9    PEAK= 2 DEG TS= .15  SEC TN= .329364 SEC
 .266931        .343533        .27652         .999711        11.5545
--------------------------------------------------------------------
 .5   CPS D= .9    PEAK= 4 DEG TS= .221 SEC TN= .329364 SEC
 .638197        .687066        .647556        .994605        19.7336
--------------------------------------------------------------------
 .5   CPS D= .9    PEAK= 6 DEG TS= .251 SEC TN= .329364 SEC
 .994383        1.0306         1.00355        .992878        27.5983
--------------------------------------------------------------------
 .5   CPS D= .9    PEAK= 8 DEG TS= .2675   SEC TN= .329364 SEC
 1.34496        1.37413        1.35402        .99818         35.3789
--------------------------------------------------------------------
 .5   CPS D= .9    PEAK= 10   DEG TS= .2785   SEC TN= .329364 SEC
 1.69353        1.71766        1.70238        .994837        43.066
```

TABLE I. (Continued)

ERRØR AT TS [DEG.]	ERRØR AT TN [DEG.]	ERRØR AT TS+10 MS. [DEG.]	ERRØR RATE AT TS [DEG./SEC.]	ERRØR ACCEL. DEG/SEC/SEC
1 CPS D= .5	PEAK= 2 DEG TS= .168 SEC TN= .19245 SEC			
.934471	.946207	.942189	.98334	6.17851
1 CPS D= .5	PEAK= 4 DEG TS= .18 SEC TN= .19245 SEC			
1.88647	1.89241	1.89219	.966502	6.07271
1 CPS D= .5	PEAK= 6 DEG TS= .184 SEC TN= .19245 SEC			
2.83455	2.83862	2.83849	.972086	6.1078
1 CPS D= .5	PEAK= 8 DEG TS= .186 SEC TN= .19245 SEC			
3.78168	3.78483	3.78389	.983293	6.17821
1 CPS D= .5	PEAK= 10 DEG TS= .1875 SEC TN= .19245 SEC			
4.72872	4.73104	4.72868	.938924	5.89943
1 CPS D= .7	PEAK= 2 DEG TS= .144 SEC TN= .177264 SEC			
.639216	.654966	.64748	.991915	32.9512
1 CPS D= .7	PEAK= 4 DEG TS= .1595 SEC TN= .177264 SEC			
1.30134	1.30993	1.30834	.992236	58.048
1 CPS D= .7	PEAK= 6 DEG TS= .1655 SEC TN= .177264 SEC			
1.95934	1.9649	1.96478	.960539	82.707
1 CPS D= .7	PEAK= 8 DEG TS= .168 SEC TN= .177264 SEC			
2.6153	2.61986	2.61984	.997692	107.894
1 CPS D= .7	PEAK= 10 DEG TS= .17 SEC TN= .177264 SEC			
3.27135	3.27483	3.27435	.969413	132.509
1 CPS D= .9	PEAK= 2 DEG TS= .1105 SEC TN= .164682 SEC			
.319099	.343533	.32789	.994605	39.4671
1 CPS D= .9	PEAK= 4 DEG TS= .134 SEC TN= .164682 SEC			
.67273	.687066	.680794	.988733	70.6729
1 CPS D= .9	PEAK= 6 DEG TS= .143 SEC TN= .164682 SEC			
1.02022	1.0306	1.0277	.996639	101.491
1 CPS D= .9	PEAK= 8 DEG TS= .148 SEC TN= .164682 SEC			
1.36609	1.37413	1.37289	.994144	132.049
1 CPS D= .9	PEAK= 10 DEG TS= .1515 SEC TN= .164682 SEC			
1.71147	1.71766	1.71732	.962837	162.238

TABLE I. (Continued)

EXPØ2 17:19 MØN. 06/01/70

ERRØR AT TS [DEG.]	ERRØR AT TN [DEG.]	ERRØR AT TS+10 MS. [DEG.]	ERRØR RATE AT TS [DEG./SEC.]	ERRØR ACCEL. DEG/SEC/SEC
2 CPS D= .5	PEAK= 2 DEG TS= .09 SEC TN= .096225 SEC			
.943237	.946207	.945159	.966502	12.1454
2 CPS D= .5	PEAK= 4 DEG TS= .093 SEC TN= .096225 SEC			
1.89084	1.89241	1.88575	.983293	12.3564
2 CPS D= .5	PEAK= 6 DEG TS= .0945 SEC TN= .096225 SEC			
2.83795	2.83862	2.82381	.781645	9.82244
2 CPS D= .5	PEAK= 8 DEG TS= .095 SEC TN= .096225 SEC			
3.78438	3.78483	3.76266	.737816	9.27167
2 CPS D= .5	PEAK= 10 DEG TS= .095 SEC TN= .096225 SEC			
4.73047	4.73104	4.70333	.92227	11.5896
2 CPS D= .7	PEAK= 2 DEG TS= .08 SEC TN= 8.86319E-02 SEC			
.650914	.654966	.65487	.962245	115.605
2 CPS D= .7	PEAK= 4 DEG TS= .0885 SEC TN= 8.86319E-02 SEC			
1.30993	1.30993	1.30043	2.73134E-02	199.062
2 CPS D= .7	PEAK= 6 DEG TS= .3915 SEC TN= 8.86319E-02 SEC			
-6.96272E-02	1.9649	-7.81629E-02	-.989965	-27.9717
2 CPS D= .7	PEAK= 8 DEG TS= .4005 SEC TN= 8.86319E-02 SEC			
-.103237	2.61986	-.111589	-.997303	-33.1959
STA				
2 CPS D= .7	PEAK= 10 DEG TS= .407 SEC TN= 8.86319E-02 SEC			
-.13628	3.27483	-.144256	-.983043	-37.9543
2 CPS D= .9	PEAK= 2 DEG TS= .067 SEC TN= 8.23409E-02 SEC			
.336365	.343533	.342727	.988733	141.346
2 CPS D= .9	PEAK= 4 DEG TS= .346 SEC TN= 8.23409E-02 SEC			
7.57397E-02	.687066	6.62934E-02	-.996124	4.25933
2 CPS D= .9	PEAK= 6 DEG TS= .382 SEC TN= 8.23409E-02 SEC			
6.91647E-02	1.0306	5.97322E-02	-.999971	1.84657
2 CPS D= .9	PEAK= 8 DEG TS= .406 SEC TN= 8.23409E-02 SEC			
6.43951E-02	1.37413	5.50138E-02	-.99816	.200398
2 CPS D= .9	PEAK= 10 DEG TS= .4235 SEC TN= 8.23409E-02 SEC			
6.09009E-02	1.71766	5.15387E-02	-.998887	-1.05203

TABLE I. (Continued)

EXP[illegible] 8:50 . TUES. 06/02/70

ERROR AT TS [DEG.]	ERROR AT TN [DEG.]	ERROR AT TS+10 MS. [DEG.]	ERROR RATE AT TS [DEG./SEC.]	ERROR ACCEL. DEG/SEC/SEC
3 CPS D= .5	PEAK= 2 DEG TS= .0615 SEC	TN= .06415 SEC		
.946207	.946207	.937545	.913168	17.2128
3 CPS D= .5	PEAK= 4 DEG TS= .063 SEC	TN= .06415 SEC		
1.89197	1.89241	1.86755	.781645	14.7337
3 CPS D= .5	PEAK= 6 DEG TS= .0635 SEC	TN= .06415 SEC		
2.83841	2.83862	2.79712	.659623	12.4336
3 CPS D= .5	PEAK= 8 DEG TS= .0635 SEC	TN= .06415 SEC		
3.78454	3.78483	3.7295	.879498	16.5781
3 CPS D= .5	PEAK= 10 DEG TS= .064 SEC	TN= .06415 SEC		
4.73102	4.73104	4.65453	.252552	4.7605
3 CPS D= .7	PEAK= 2 DEG TS= .0635 SEC	TN= 5.90879E-02 SEC		
.652798	.654866	.633719	-.968112	157.114
3 CPS D= .7	PEAK= 4 DEG TS= .261 SEC	TN= 5.90879E-02 SEC		
-4.64188E-02	1.30993	-5.43135E-02	-.989965	-41.9575
3 CPS D= .7	PEAK= 6 DEG TS= .2695 SEC	TN= 5.90879E-02 SEC		
-8.00569E-02	1.9649	-8.73418E-02	-.982611	-53.2374
3 CPS D= .7	PEAK= 8 DEG TS= .274 SEC	TN= 5.90879E-02 SEC		
-.111836	2.61986	-.11883	-.998364	-64.5234
3 CPS D= .7	PEAK= 10 DEG TS= .2775 SEC	TN= 5.90879E-02 SEC		
-.143781	3.27483	-.149913	-.969229	-74.6202
3 CPS D= .9	PEAK= 2 DEG TS= .212 SEC	TN= 5.48939E-02 SEC		
5.40389E-02	.343533	4.48064E-02	-.993451	9.30172
3 CPS D= .9	PEAK= 4 DEG TS= .255 SEC	TN= 5.48939E-02 SEC		
4.57774E-02	.687066	3.66702E-02	-.994136	2.70332
3 CPS D= .9	PEAK= 6 DEG TS= .277 SEC	TN= 5.48939E-02 SEC		
4.15914E-02	1.0306	3.25314E-02	-.996424	-.705898
3 CPS D= .9	PEAK= 8 DEG TS= .2915 SEC	TN= 5.48939E-02 SEC		
3.86685E-02	1.37413	2.96296E-02	-.999417	-3.13376
3 CPS D= .9	PEAK= 10 DEG TS= .3025 SEC	TN= 5.48939E-02 SEC		
3.60397E-02	1.71766	2.70647E-02	-.995736	-5.1082

TABLE I. (Continued)

ØXPØ2 15:12 WED. 05/06/70

ØERRØR AT TS [DEG.\	ERRØR AT TN [DEG.]	ERRØR AT TS310 MS. [DEG.]	ERRØR RATE AT TS [DEG./SEC.L	ERRØR ACCEL. AT TS DEG/SEC/SEC
4 CPS	DZ .5	PEAK= DEG	TS= .184 SEC	TN=
4.81125E-02	SEC			
-.150539	.946207	-.154148	-.910478	117.971
4 CPS	D= .5	PEAK= 4 DEG	TS= .192 SEC	TN=
4.81125E-02	SEC			
-.308507	1.89241	-.300349	-8.82109E-02	197.087
4 CPS	D= .5	PEAK= 6 DEG	TS= .32 SEC	TN=
4.81125E-02	SEC			
6.77992E-02	2.83862	7.42902E-02	.966146	-67.1076
4 CPS	D= .5	PEAK= 8 DEG	TS= .324 SEC	TN=
4.81125E-02	SEC			
9.48514E-02	3.78483	.100348	.941971	-83.5876
4 CPS	D= .5	PEAK= 10 DEG	TS= .326 SEC	TN=
4.81125E-02	SEC			
.120713	4.73104	.125726	.972283	-100.685
4 CPS	D= .7	PEAK= 2 DEG	TS= .188 SEC	TN=
4.43159E-02	SEC			
-1.68844E-02	.654966	-2.45999E-02	-.981669	45.2059
4 CPS	D= .7	PEAK= 4 DEG	TS= .201 SEC	TN=
4.43159E-02	SEC			
-5.23474E-02	1.30993	-5.87796E-02	-.947023	66.3873
4 CPS	D= .7	PEAK= 6 DEG	TS= .206 SEC	TN=
4.43159E-02	SEC			
-8.44326E-02	1.9649	-9.00283E-02	-.954596	86.9205
4 CPS	D= .7	PEAK= 8 DEG	TS= .209 SEC	TN=
4.43159E-02	SEC			
-.115888	2.61986	-.120477	-.939654	106.264
4 CPS	D= .7	PEAK= 10 DEG	TS= .211 SEC	TN=
4.43159E-02	SEC			
-.146949	3.27483	-.150476	-.916698	125.076

TABLE I. (Continued)

4 CPS D= .9 PEAK= 2 DEG TS= .043 SEC TN=
4.11705E-02 SEC
.34318 .343533 .330822 -.380881 -199.54

---

4 CPS D=] .9 PEAK= 4 DEG TS= .203 SEC TN-
4.11705E-02 SEC
3.21975E-02 .687066 2.33775E-02 -.99816 24.818

---

4 CPS D= .9 PEAK= 6 DEG TS= .219 SEC TN=
4.11705E-02 SEC
2.86285E-02 1.0306 1.99754E-02 -.989373 26.6749

---

4 CPS D=L .9 PEAK= 8 DEG TS= .23 SEC TN=
4.11705E-02 SEC
2.56478E-02 1.37413 .017213 -.972118 27.7771

---

4 CPS D= .9 PEAK= 10 DEG TS= .237 SEC TN=
4.11705E-02 SEC
2.43598E-02 1.71766 1.58101E-02 -.990968 29.4433

ABSØLUTE VALUE RAISED TØ PØWER IN 210

DXPØ2 16:06 WED. 05/06/70

ERRØR AT TS [DEG.]	ERRØR AT TN [DEG.]	ERRØR AT TS+10 MS. [DEG.]	ERRØR RATE AT TS [DEG./SEC.]	ERRØR ACCEL.N AT TS DEG/SEC/SEC

---

8 CPS D= .5 PEAK= 2 DEG TS= .157 SEC TN=
2.40563E-02 SEC
2.02522E-02 .946207 .025087 .925036 -97.6669

---

8 CPS D= .5 PEAK= 4 DEG TS= .162 SEC TN=
2.40563E-02 SEC
4.74257E-02 1.89241 4.95237E-02 .941971 -167.175

---

8 CPS
2.40563E-02 SEC
7.54355E-02 2.83862 6.80552E-02 7.58205E-02 -194.408

---

8 CPS D= .5 PEAK= 8 DEG TS= .224 SEC TN=
2.40563E-02 SEC
-9.20220E-03 3.78483 -1.54113E-02 -.952853 71.1461

---

8 CPS D= .5 PEAK= 10 DEG TS= .227 SEC TN=
2.40563E-02 SEC
-1.46828E-02 4.73104 -2.01533E-02 -.931486 83.9195

TABLE I. (Continued)

8 CPS	D= .7	PEAK= 2 DEG	TS= .101 SEC	TN= .022158 SEC
-2.66308E-02	.654966	-3.00558D-02	-.881501	129.319
8 CPS	D= .7	PEAK= 4 DEG	TS= .106 SEC	TN= .022158 SEC
-5.91215E-02	1.30993	-5.76239E-02	-.634819	194.051
8 CPS	D= .7	PEAK= 6 DEG	TS= .112 SEC	TN= .022158 SEC
-8.97777E-02	1.9649	-7.75053E-02	.488463	192.46
8 CPS	D= .7	PEAK= 8 DEG	TS= .167 SEC	TN= .022158 SEC
-6.38504E-03	2.61986	1.11277E-03	.997155	-54.0389
8 CPS	D= .7	PEAK= 10 DEG	TS= .171 SEC	TN= .022158 SEC
-3.51825E-03	3.27483	3.64315E-03	.989617	-60.7517
8 CPS	D= .9	PEAK= 2 DEG	TS= .102 SEC	TN=
2.05852E-02	SEC			
1.56059E-02	.343533	8.00106E-03	-.973587	48.6581
8 CPS	D= .9	PEAK= 4 DEG	TS= .115 SEC	TN=
2.05852E-02	SEC			
1.28239E-02	.687066	5.48883E-03	-.972118	55.5541
8 CPS	D= .9	PEAK= 6 DEG	TS= .122 SEC	TN=
2.05852E-02	SEC			
1.08632E-02	1.0306	3.77750E-03	-.961699	59.5652
8 CPS	D= .9	PEAK= 8 DEG	TS= .126 SEC	TN=
2.05852E-02	SEC			
9.95015E-03	1.37413	2.74275E-03	-.994529	64.8426
8 CPS	D= .9	PEAK= 10 DEG	TS= .13 SEC	TN=
2.05852E-02	SEC			
8.07057E-03	1.71766	1.31584E-03	-.950682	65.6244
12 CPS	D=] .5	PEAK= 2 DEG	TS= .107 SEC	TN=
1.60375E-02	SEC			
2.29107E-02	.946207	2.37356E-02	.899579	-198.071
12 CPS	D= .5	PEAK= 4 DEG	TS= .146 SEC	TN=
1.60375E-02	SEC			
-1.76382E-03	1.89241	-7.70567E-03	-.990324	84.6958
12 CPS	D= .5	PEAK= 6 DEG	TS= .15 SEC	TN=
1.60375E-02	SEC			
-7.58976E-03	2.83862	-.012296	-.9926	117.987
12 CPS	D= .5	PEAK= 8 DEG	TS= .153 SEC	TN=
1.60375E-02	SEC			
-1.34035E-02	3.78483	-1.61012E-02	-.873367	142.047
12 CPS	D= .5	PEAK= 10 DEG	TS= .154 SEC	TN=]
1.60375E-02	SEC			
-1.77585E-02	4.73104	-1.98054E-02	-.917814	170.157

TABLE I. (Continued)

12 CPS	D=] .7	PEAK= 2 DEG	TS= .072 SEC	TN= .014772 SEC
-3.00094E-02	.654966	-2.52354E-02	-.202756	192.003
12 CPS	D= .7	PEAK= 4 DEG	TS= .108 SEC	TN= .014772 SEC
-6.03583E-03	1.30993	5.56385E-04	.961688	-67.2004
12 CPS	D= .7	PEAK= 6 DEG	TS= .113 SEC	TN= .014772 SEC
-3.04321E-03	1.9649	3.03103E-03	.974451	-85.5603
12 CPS	D= .7	PEAK= 8 DEG	TS= .116 SEC	TN= .014772 SEC
-6.51769E-04	2.61986	4.97427E-03	.978547	-99.5877
12 CPS	D= .7	PEAK= 10 DEG	TS= .118 SEC	TN= .014772 SEC
1.39096E-03	3.27483	6.65993E-03	.986634	-112.054
12 CPS	D= .9	PEAK= 2 DEG	TS= .073 SEC	TN=
1.37235E-02	SEC			
9.54282E-03	.3435331	2.87920E-03	-.989373	80.0246
12 CPS	D= .9	PEAK= 4 DEG	TS= .081 SEC	TN=
1.37235E-02	SEC			
7.56772E-03	.687066	1.25064E-03	-.991854	91.5896
12 CPS	D= .9	PEAK= 6 DEG	TS= .086 SEC	TN=]
1.37235E-02	SEC			
5.43279E-03	1.0306	-1.19841E-04	-.91629	93.4711
12 CPS	D= .9	PEAK= 8 DEG	TS= .088 SEC	TN=
1.37235E-02	SEC			
5.03667E-03	1.37413	-8.19028E-04	-.991562	105.939
12 CPS	D= .9	PEAK= 10 DEG	TS= .09 SEC	TN=
1.37235E-02	SEC			
4.06769E-03	1.71766	-1.63160E-03	-.995509	111.983
16 CPS	D= .5	PEAK= 2 DEG	TS= .087 SEC	TN=
1.20281E-02	SEC			
.024245	.946207	.01267	-.612725	-183.434
16 CPS	D= .5	PEAK=] 4 DEG	TS= .112 SEC	TN=
1.20281E-02	SEC			
-4.60110E-03	1.89241	-8.08526E-03	-.952853	142.292
16 CPS	D= .5	PEAK= 6 DEG	S= .115 SEC	TN=
1.20281E-02	SEC			
-.010265	2.83862	-1.11335E-02	-.826339	186.816
16 CPS	D= .5	PEAK= 8 DEG	TS= .119 SEC	TN=
1.20281E-02	SEC			
-1.62594E-02	3.78483	-1.18813E-02	-.226047	187.049
16 CPS	D= .5	PEAK= 10 DEG	TS= .121 SEC	TN=
1.20281E-02	SEC			
-2.04493E-02	4.73104	-1.26698E-02	.143535	192.241

TABLE I. (Continued)

16 CPS	D= .7	PEAK= 2 DEG	TS= .056 SEC	TN= .011079 SEC
-.028812	.654966	-1.64641E-02	.763972	183.663
16 CPS	D=] .7	PEAK= 4 DEG	TS= .084 SEC	TN, .011079 SEC
-2.70734E-03	1.30993	2.40582E-03	.943766	-105.467
16 CPS	D= .7	PEAK= 6 DEG	TS= .087 SEC	TN= .011079 SEC
-4.88826E-04	1.9649	4.09790E-03	.978547	-132.784
16 CPS	D= .7	PEAK=8 DEG	TS= .089 SEC	TN= .011079 SEC
1.61930E-03	2.61986	5.53625E-03	.9742	-153.478
16 CPS	D5 .7	PEAK= 10 DEG	TS= .091 SEC	TN= .011079 SEC
4.09540E-03	3.27483	6.74557E-03	.86319	-162.878
16 CPS	D= .9	PEAK= 2 DEG	TS= .058 SEC	TN=
1.02926E-02	SEC			
5.93956E-03	.343533	6.85687E-04	-.917834	106.059
16 CPS	D= .9	PEAK= DEG	TS= .063 SEC	TN
1.02926E-02	SEC			
4.97507E-03	.687066	-3.10101E-04	-.994529	129.685
16 CPS	D= .9	PEAK= 6 DEG	TS= .066 SEC	TN=
1.02926E-02	SEC			
3.77750E-03	1.0306	-1.16180E-03	-.991562	141.252
16 CPS	D= .9	PEAK= 8 DEG	TS= .068 SEC	TN=
1.02926E-02	SEC			
2.74275E-03	1.37413	-1.87997E-0	150.426	
16 CPS	D= .9	PEAK= 10 DEG	TS= .07 SEC	TN=
1.02926E-02	SEC			
1.31584E-03	1.71766	-2.55854E-03	-.89512	148.679
20 CPS	D= .5	PEAK= 2 DEG	TS= .087 SEC	TN=
9.62250E-03	SEC			
-3.65522E-04	.946207	-4.08150E-03	-.896105	118.38
20 CPS	D= .5	PEAK= 4 DEG	TS= .092 SEC	TN=
9.62250E-03	SEC			
-6.84336E-03	1.89241	-6.55148E-03	-.688616	194.6
20 CPS	D= .5	PEAK= 6 DEG	TS= .096 SEC	TN=
9.62250E-03	SEC			
-.012296	2.83862	-6.59119E-03	-4.43328E-02	199.741
20 CPS	D= .5	PEAK= 8 DEG	TS= .099 SEC	TN=
9.62250E-03	SEC			
-1.55193E-02	3.78483	-5.49413E-03	.594579	170.354
20 CPS	D= .5	PEAK= 10 DEG	TS= .1 SEC	TN=
9.62250E-03	SEC			
-1.85558E-02	4.73104	-5.58655E-03	.937182	175.252

TABLE I. (Continued)

20 CPS	D= .7	PEAK= 2 DEG	TS= .063 SEC	TN=
8.86319E-03	SEC			
-4.61492E-03	.654966	8.61229E-04	.974626	-98.5893
20 CPS	D= .7	PEAK= 4 DEG	TS= .069 SEC	TN=
8.86319E-03	SEC			
-8.40466E-04	1.30993	2.77003E-03	.9005	-145.152
20 CPS	D= .7	PEAK= 6 DEG	TS= .071 SEC	TN=]
8.86319E-03	SEC			
1.02819E-03	1.9649	4.02525E-03	.949628	-183.304
20 CPS	D= .7	PEAK= 8 DEG	TS= .073 SEC	TN=
8.86319E-03	SEC			
3.44492E-03	2.61986	4.96097E-03	.822913	-199.174
20 CPS	D= .7	PEAK= 10 DEG	S= .075 SEC	TN=
8.86319E-03	SEC			
5.90156E-03	3.27483	5.51576E-03	.584431	-196.012
20 CPS	D=] .9	PEAK= 2 DEG	TS= .048 SEC	TN=
8.23409E-03	SEC			
4.30326E-03	.343533	-1.00227E-04	-.905756	136.923
20 CPS	D= .9	PEAK= 4 DEG	TS= .052 SEC	TN=
8.23409E-03	SEC			
3.22823E-03	.687066	-9.07290E-04	-.950682	164.061
20 CPS	D= .9	PEAK= 6 DEG	TS= .054 SEC	TN=]
8.23409E-03	SEC			
2.44061E-03	1.0306	-1.53513E-03	-.995509	186.638
20 CPS	D= .9	PEAK= 8 DEG	TS= .056 SEC	TN=
8.23409E-03	SEC			
1.05267-0	-2.09112E-03	-.89512	185.848	
20 CPS	D=] .9	PEAK= 10 DEG	TS= .057 SEC	TN=
8.23409E-03	SEC			
3.07454E-04	1.71766	-2.58025E-03	-.903342	199.476

APPENDIX D LISTING OF REMOTE DRIVING AIDS COMPUTER PROGRAM AND SIMULATION USED TO GENERATE TEST CASES (TRAVERSAL THROUGH A CRATER FIELD)

```
$      IDENT    366,52120,2064B,65054,COX
$      OPTION   FORTRAN
$      FORTRAN
      DIMENSION VRT(200),VPT(200),IVBTP(200),CAZT(200),CELT(200),ICAMTP(
     1200),CAZC(200),CELC(200),HC(200),VC(200),X(200),Y(200),Z(200),
     2DELX(200),DELY(200),DELZ(200),YT(200),VT(200),ITP(200),
     3CX(200),CY(200),CZ(200),RJSHA(200),FWLSX(11),FWLSY(11), FWRSX(11),
     4FWRSY(11),RMWLSX(11),RMWLSY(11),RMWRSX(11),RMWRSY(11),POPLX(11),
     5POPLY(11),POPRX(11),POPRY(11),GLP10X(11),GLP10Y(11),GLP20X(11),
     6GLP20Y(11),GLM10X(11),GLM10Y(11),GLM20X(11),GLM20Y(11),PRPLX(200),
     7PRPLY(200),PRPRX(200),PRPRY(200),       R(7),      GCRTX(7),GCRTY(7
     8),GCX(7, 61),GCY(7, 61),HCR(49),RC(49),RKC(49),CRATX(49,91),CRATY(
     949,91),HLX(91),HLY(91),DELCX(200),DELCY(200),DELCZ(200)
     A                     ,RJSPLX(11),RJSPLY(11),RJSPRX(11),RJSPRY(11)
      DIMENSION IPRA(11)
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      COMMON/LINCOM/X1,Y1,Z1,X2,Y2,NN
      DATA(IPRA(I),I=1,11)/41,45,49,53,61,69,77,85,93,101,109/
      DO 38 I=1,49
      READ(5,39)HCR(I),RKC(I),RC(I)
   39 FORMAT(3F12.0)
   38 CONTINUE
      DO 11 I=1,22
      YT(I)=0.
      VT(I)=.125
      ITP(I)=1
      VRT(I)=0.
      VPT(I)=0.
      IVBTP(I)=1
      CAZT(I)=0.
      CELT(I)=-10.
      ICAMTP(I)=1
      CX(I)=0.
      CY(I)=0.
   18 CZ(I)=0.
      RJSHA(I)=0.
   11 CONTINUE
      DO 20 I=23,40
      RJSHA(I)=0.
   20 CONTINUE
      NN=11
      PDLY=6.
      TMDLY=1.3
      CMDLY=4.
      TMR=4.
      D1=.3
      D2=.611
      D3=.733
      D4=.203
      D5=.685
      D6=.457
      D7=.882
      D8=0.
      D9=0.
      D10=1.7
```

```
      D11=.1015
      GCRTX(6)=D8+D11
      GCRTY(6)=D9
      GCRTX(7)=D8+D11
      GCRTY(7)=D9
      HFOV=60.
      VFOV=40.
      RA=1.
      CS=.7
      DTR=.0174533
      TERM10=1.*DTR
      RVPICS=.254
      RSCF=RVPICS/(2.*D11*TAN(.5*VFOV*DTR) )
      RHPICS=RSCF*2.*D11*TAN(.5*HFOV*DTR)
      RTMR=1./TMR
      R(1)=5.
      R(2)=10.
      R(3)=30.
      R(4)=100.
      R(5)=0.
      QRA=TAN(RA*DTR)
C******** ATEM*R(6)**2 + BTEM*R(6) + CTEM = 0
      ATEM=QRA
      BTEM=CS*QRA
      CTEM=(D1+D10)*((D1+D10)*QRA-CS)
      R(6)=(-BTEM+SQRT(BTEM**2 -4.*ATEM*CTEM) )/(2.*ATEM)
      R(7)=R(6)+CS
      CX(22)=1./24.
      CY(22)=1./24.
      CZ(22)=0.
C******** ROUND DOWN FOR ISPTM, ROUND UP FOR ISPC
      ISPTM=TMR*(PDLY-TMDLY)+.001
      ISPC=TMR*(PDLY+CMDLY)+.999
      ISPCP1=ISPC+1
      D1D10S=(D1+D10)**2
      SINHFV=SIN(.5*HFOV*DTR)
      RS5=0.
      ILPR=0
      CALL PLOTE(10.)
      DO 900 IJ=1,11
      IPR=IPRA(IJ)
      X(1)=0.
      Y(1)=0.
      Z(1)=0.
      IL1=IPR-ILPR
      ILPR=IPR
      IF(IL1.GT.  ISPC)GO TO 100
      DO 53 J=2,ISPCP1
      JPIL1=J+IL1
      DELX(J)=DELX(JPIL1)
      DELY(J)=DELY(JPIL1)
      DELZ(J)=DELZ(JPIL1)
   53 CONTINUE
      GO TO 550
  100 DO 501 J=2,ISPCP1
      IT=IPR-ISPTM +J-2
      IF(IT.GE.IPR)GO TO 230
```

```
      READ(5,2)YT(IT),VT(IT),ITP(IT)
    2 FORMAT(2F12.0,I2)
      WRITE(6,60)YT(IT),VT(IT)
      IF(ITP(IT).LT.1)GO TO 230
      READ(5,2)VRT(IT),VPT(IT),IVBTP(IT)
      WRITE(6,60)VRT(IT),VPT(IT)
  150 PVH=YT(IT)
      PVV=VT(IT)
      PVP=VPT(IT)
      GO TO 400
  230 IT21=IPR-ISPC +J-2
      READ(5,2)HC(IT21),VC(IT21)
      WRITE(6,60)HC(IT21),VC(IT21)
      PVH=HC(IT21)
      PVV=VC(IT21)
      PVP=0.
  400 TEMP1=PTMR*PVV
      TEMP2=PVH*DTR
      DELX(J)=TEMP1*COS(TEMP2)
      DELY(J)=TEMP1*SIN(TEMP2)
      DELZ(J)=-DELX(J)*TAN(PVP*DTR)
      IF(IT.GT.IPR-1)GO TO 501
      DELCX(IT)=DELX(J)
      DELCY(IT)=DELY(J)
      DELCZ(IT)=DELZ(J)
  501 CONTINUE
  550 CONTINUE
      DO 301 J=1,4
      IS3=IPR-ISPTM +J-1
      IF(IVBTP(IS3).EQ.1)GO TO 320
  301 CONTINUE
      GO TO 340
  320 VR=VRT(IS3)
      VP=VPT(IS3)
      VY=YT(IS3)
      GO TO 360
  340 VR=0.
      VP=0.
      ITEM1=IPR-ISPC
      VY=HC(ITEM1)
  360 ITEM=IPR-ISPTM
      READ(5,2)CAZT(ITEM),CELT(ITEM),ICAMTP(ITEM)
      WRITE(6,60)CAZT(ITEM),CELT(ITEM)
      IF(ICAMTP(ITEM).LT.1)GO TO 450
      CEL=CELT(ITEM)
      CAZ=CAZT(ITEM)
      GO TO 500
  450 ITEM1=IPR-ISPC
      READ(5,2)CAZC(ITEM1),CELC(ITEM1)
      CEL=CELC(ITEM1)
      CAZ=CAZC(ITEM1)
  500 TEM=VP*DTR
      CT=COS(TEM)
      ST=SIN(TEM)
      TEM=VR*DTR
      CP=COS(TEM)
      SP=SIN(TEM)
```

```
      TEM=CAZ*DTR
      CE=COS(TEM)
      SE=SIN(TEM)
      TEM=CEL*DTR
      CG=COS(TEM)
      SG=SIN(TEM)
  600 IPRP3=IPR+3
      IF(IPR.GE.53)IPRP3=IPR+7
      KK=0
      DO 6000 ICL=IPR,IPRP3
      ITA=ICL-IPR
      ITAP42= ITA +ISPC+2
      ITAP21= ITA +ISPTM+2
      READ(5,2)YT(ICL),VT(ICL),ITP(ICL)
      WRITE(6,60)YT(ICL),VT(ICL)
   60 FORMAT(/,12E10.3)
      IF(ITP(ICL).LT.1)GO TO 220
      READ(5,2)VRT(ICL),VPT(ICL),IVBTP(ICL)
      WRITE(6,60)VRT(ICL),VPT(ICL)
      IF(IVBTP(ICL).LT.1)GO TO 220
      PVH=YT(ICL)
      PVV=VT(ICL)
      PVP=VPT(ICL)
      TEMP1=RTMR*PVV
      TEMP2=PVH*DTR
      DELX(ITAP21)=TEMP1*COS(TEMP2)
      DELY(ITAP21)=TEMP1*SIN(TEMP2)
      DELZ(ITAP21)=-DELX(ITAP21)*TAN(PVP*DTR)
      DELCX(ICL)=DELX(ITAP21)
      DELCY(ICL)=DELY(ITAP21)
      DELCZ(ICL)=DELZ(ITAP21)
  220 READ(5,2)HC(ICL),VC(ICL)
      WRITE(6,60)HC(ICL),VC(ICL)
      PVH=HC(ICL)
      PVV=VC(ICL)
      PVP=0.
      TEMP1=RTMR*PVV
      TEMP2=PVH*DTR
      DELX(ITAP42)=TEMP1*COS(TEMP2)
      DELY(ITAP42)=TEMP1*SIN(TEMP2)
      DELZ(ITAP42)=0.
      IF(ICL.GT.IPR)GO TO 300
      GO TO 410
  300 IF(8*(KK/8).NE.KK)GO TO 35
  410 DO 451 J=2,ITAP42
      X(J)=DELX(J)+X(J-1)
      Y(J)=DELY(J)+Y(J-1)
  451 Z(J)=DELZ(J)+Z(J-1)
      DO 101 J=2,ITAP21
      IT=IPR-ISPTM +J-2
      CX(IT)=CX(IT-1)+DELCX(IT)
      CY(IT)=CY(IT-1)+DELCY(IT)
  101 CZ(IT)=CZ(IT-1)+DELCZ(IT)
      X10PTA=X(ITAP42)
      Y10PTA=Y(ITAP42)
      Z10PTA=Z(ITAP42)
      READ(5,2)RJSHA(ICL)
```

```
      RJSH=RJSHA(ICL)
      WRITE(6,60)RJSHA(ICL)
      TEMP1=X1OPTA+D3
      TEMP6=Y1OPTA-.5*D2
      TEMP7=Y1OPTA+.5*D2
      TEMP8=Y1OPTA-.5*D4
      CA=1.
      SA=0.
      CALL PREGH
      X1=TEMP1
      Y1=TEMP6
      Z1=Z1OPTA
      X2=TEMP1+2300.*COS(RJSH*DTR)
      Y2=Y1+2300.*SIN(RJSH*DTR)
      CALL LINE(RJSPLX,RJSPLY)
      Y1=TEMP7
      Y2=Y2+D2
      CALL LINE(RJSPRX,RJSPRY)
      TEM2=VY*DTR
      CA=COS(TEM2)
      SA=SIN(TEM2)
      CALL PREGH
      X2=TEMP1
      Y1=TEMP8-.5*D2
      Y2=Y1+D4
      CALL LINE(FWLSX,FWLSY)
      Y1=Y1+D2
      Y2=Y2+D2
      CALL LINE(FWRSX,FWRSY)
      X1=X1-D5
      X2=X1
      Y1=Y1-D2
      Y2=Y2-D2
      CALL LINE(RMWLSX,RMWLSY)
      Y1=Y1+D2
      Y2=Y2+D2
      CALL LINE(RMWRSX,RMWRSY)
      IL5=ITAP21
      IF(ITA.EQ.0)IL5=1
      DO 302 I=IL5,ITAP42
      TEMP1=D3+X(I)
      CALL GH(TEMP1,Y(I)-.5*D2,Z(I),PRPLX(I),PRPLY(I))
      CALL GH(TEMP1,Y(I)+.5*D2,Z(I),PRPRX(I),PRPRY(I))
  302 CONTINUE
      TEMP1=X1OPTA+D3
      X1=TEMP1
      X2=TEMP1+2300.*COS(HC(ICL)*DTR)
      Y1=TEMP6
      Y2=TEMP6+2300.*SIN(HC(ICL)*DTR)
      CALL LINE(POPLX,POPLY)
      Y1=TEMP7
      Y2=Y2+D2
      CALL LINE(POPRX,POPRY)
      X1=TEMP1
      TEM1=(HC(ICL)+10.)*DTR
      TEM2=TEM1-20.*DTR
      X2=X1+2300.*COS(TEM1)
```

```
      Y1=Y1OPTA
      Y2=Y1+2300.*SIN(TEM1)
      CALL LINE(GLP1OX,GLP1OY)
      X2=X1+2300.*COS(TEM2)
      Y2=Y1+2300.*SIN(TEM2)
      CALL LINE(GLM1OX,GLM1OY)
      TEM1=(HC(ICL)+20.)*DTR
      TEM2=TEM1-40.*DTR
      X2=X1+2300.*COS(TEM1)
      Y2=Y1+2300.*SIN(TEM1)
      CALL LINE(GLP2OX,GLP2OY)
      X2=X1+2300.*COS(TEM2)
      Y2=Y1+2300.*SIN(TEM2)
      CALL LINE(GLM2OX,GLM2OY)
      DO 31 I=1,5
      GCRTX(I)=TEMP1
      GCRTY(I)=Y1OPTA
   31 CONTINUE
      TERM9=DTR*(60.-HC(ICL))
      DO 30 J=1,61
      TERM1=TERM9+TERM10*FLOAT(J-1)
      TERM2=SIN(TERM1)
      TERM3=COS(TERM1)
      DO 30 I=1,7
      IF(R(I).LT.1.E-6)GO TO 30
      TEMP=Z1OPTA
      IF(I.GT.5)TEMP=0.
      CALL GH(GCRTX(I)+R(I)*TERM2,GCRTY(I)+R(I)*TERM3,TEMP,GCX(I,J),
     1GCY(I,J))
   30 CONTINUE
      IF(IPR.LT.49)GO TO 50
      CALL PLT(FWLSX,FWLSY,11)
      CALL PLT(FWRSX,FWRSY,11)
      CALL PLT(RMWLSX,RMWLSY,11)
      CALL PLT(RMWRSX,RMWRSY,11)
      CALL PLT(GLP1OX,GLP1OY,11)
      CALL PLT(GLP2OX,GLP2OY,11)
      CALL PLT(GLM1OX,GLM1OY,11)
      CALL PLT(GLM2OX,GLM2OY,11)
   50 CONTINUE
      IF(IPR.GE.49)GO TO 52
      DO 51 I=1,5
      DO 51 J=1,61
   51 GCX(I,J)=-1.E6
   52 CONTINUE
      CALL PLT(PRPLX,PRPLY,42)
      CALL PLT(PRPPX,PRPRY,42)
      CALL PLT2(GCX,GCY,7, 61)
      CALL PLT(POPLX,POPLY,11)
      CALL PLT(POPRX,POPRY,11)
      CALL PLT3(RJSPLX,RJSPLY,11)
      CALL PLT3(RJSPRX,RJSPRY,11)
   35 KK=KK+1
 6000 CONTINUE
      CRCHX=(RS5-1.)*(87.   *1./8.)-CX(IPR-20)
      CRCHY=(RS5-1.)*CY(IPR-20)
      DO 2100 I=1,49
```

```
      DO 2100 M=1,91
      CRATSX= HCR(I)+CRCHX+RC(I)*COS(FLOAT(M-1)*4.*DTR)
      CRATSY= RKC(I)+CRCHY+RC(I)*SIN(FLOAT(M-1)*4.*DTR)
      CRATX(I,M)=G(CRATSX,CRATSY,CZ(IPR-20))
      CRATY(I,M)=H(CRATSX,CRATSY,CZ(IPR-20))
      IF(I.GT.1)GO TO 2100
      RM=M
      TEMP=CZ(IPR-20)- 50.*COS((RM-46.)/90.)**2/ABS(RM-46.2)
      HLX(M)=G(2300.+CRCHX,-1330.+(FLOAT(M-1)/90.)*2660.+CRCHY, TEMP)
      HLY(M)=H(2300.+CRCHX,-1330.+(FLOAT(M-1)/90.)*2660.+CRCHY, TEMP)
 2100 CONTINUE
      WRITE(6,606)
  606 FORMAT(/,3X,1HX,9X,1HY,9X,1HZ)
      DO 182 I=1,50
      WRITE(6,666)X(I),Y(I),Z(I),I
  182 CONTINUE
      WRITE(6,180)
  180 FORMAT(/,3X,4HDELX,6X,4HDELY,6X,4HDELZ)
      DO 181 I=1,50
      WRITE(6,666)DELX(I),DELY(I),DELZ(I),I
  666 FORMAT(/,3E10.3,I6)
  181 CONTINUE
      WRITE(6,677)
  677 FORMAT(/,3X,5HPRPLX,5X,5HPRPLY,5X,5HPRPRX,5X,5HPRPRY)
      DO 179 I=1,50
      WRITE(6,678)PRPLX(I),PRPLY(I),PRPRX(I),PRPRY(I),I
  678 FORMAT(/,4E10.3,I6)
  179 CONTINUE
      CALL PLT2(CRATX,CRATY,49,91)
      CALL PLT(HLX,HLY,91)
      CALL PLOTE(20.)
  900 CONTINUE
      STOP
      END
$       FORTRAN DECK
CPLT
      SUBROUTINE PLT(XX,YY,N)
      DIMENSION XX(N),YY(N),X(500),Y(500)
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      XMIN=-.5*RHPICS*39.37
      XMAX= .5*RHPICS*39.37
      YMIN=0.
      YMAX=RVPICS*39.37
      DO 1 I=1,N
      X(I)=XX(I)*39.37
      Y(I)=YY(I)*39.37
      IF(X(I).LT.XMIN.OR.X(I).GT.XMAX)GO TO 1
      IF(Y(I).LT.YMIN.OR.Y(I).GT.YMAX)GO TO 1
      IF(I.EQ.1)GO TO 2
      IF(X(I-1).LT.XMIN.OR.X(I-1).GT.XMAX)GO TO 2
      IF(Y(I-1).LT.YMIN.OR.Y(I-1).GT.YMAX)GO TO 2
      CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-2)
      GO TO 1
    2 CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-1)
    1 CONTINUE
      RETURN
      END
```

```
$       FORTRAN DECK
CPLT3
      SUBROUTINE PLT3(XX,YY,N)
      DIMENSION XX(N),YY(N),X(500),Y(500)
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      XMIN=-.5*RHPICS*39.37
      XMAX= .5*RHPICS*39.37
      YMIN=0.
      YMAX=RVPICS*39.37
      DO 1 I=1,N
      X(I)=XX(I)*39.37
      Y(I)=YY(I)*39.37
      IF(X(I).LT.XMIN.OR.X(I).GT.XMAX)GO TO 1
      IF(Y(I).LT.YMIN.OR.Y(I).GT.YMAX)GO TO 1
      IF(I.EQ.1)GO TO 2
      IF(X(I-1).LT.XMIN.OR.X(I-1).GT.XMAX)GO TO 2
      IF(Y(I-1).LT.YMIN.OR.Y(I-1).GT.YMAX)GO TO 2
      IF(K.EQ.2)GO TO 2
      CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-2)
      K=2
      GO TO 1
    2 CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-1)
      K=1
    1 CONTINUE
      RETURN
      END
$       FORTRAN DECK
CPLT2
      SUBROUTINE PLT2(XX,YY,M,N)
      DIMENSION XX(M,1),YY(M,1),X(301),Y(301)
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      XMIN=-.5*RHPICS*39.37
      XMAX= .5*RHPICS*39.37
      YMIN=0.
      YMAX=RVPICS*39.37
      DO 1 K=1,M
      DO 1 I=1,N
      X(I)=XX(K,I)*39.37
      Y(I)=YY(K,I)*39.37
      IF(X(I).LT.XMIN.OR.X(I).GT.XMAX)GO TO 1
      IF(Y(I).LT.YMIN.OR.Y(I).GT.YMAX)GO TO 1
      IF(I.EQ.1)GO TO 2
      IF(X(I-1).LT.XMIN.OR.X(I-1).GT.XMAX)GO TO 2
      IF(Y(I-1).LT.YMIN.OR.Y(I-1).GT.YMAX)GO TO 2
      CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-2)
      GO TO 1
    2 CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-1)
    1 CONTINUE
      RETURN
      END
$       FORTRAN DECK
CG
      FUNCTION G(X,Y,Z)
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      XB1=CA*X+SA*Y
```

```
      YB1=-SA*X+CA*Y
      ZB1=Z+D1
      XB2=CT*XB1-ST*ZB1
      ZB2=ST*XB1+CT*ZB1
      YB3=CP*YB1+SP*ZB2
      ZB3=-SP*YB1+CP*ZB2
      XC=XB2+D8
      YC=YB3+D9
      ZC=ZB3+D10
      XD=XC*CE*CG+YC*SE*CG-ZC*SG
      YD=-XC*SE+YC*CE
      ZD=XC*CE*SG+YC*SE*SG+ZC*CG
      G=     RSCF*D11*YD/XD
      RETURN
      END
$      FORTRAN DECK
CH
      FUNCTION H(X,Y,Z)
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      X=X
      Y=Y
      Z=Z
      H=(RVPICS/2.)-(RSCF*D11*ZD/XD)
      RETURN
      END
$      FORTRAN
CLINE
      SUBROUTINE LINE(X,Y)
      DIMENSION X(1),Y(1)
      COMMON/LINCOM/X1,Y1,Z1,X2,Y2,NN
      RFN=1./FLOAT(NN-1)
      CALL GH(X1,Y1,Z1,X(1),Y(1))
      CALL GH(X2,Y2,Z1,X(NN),Y(NN))
      IF(Y(1).GE.0.)GO TO 2
      IF(Y(NN).LE.0.)GO TO 2
      X(1)=X(1)+Y(1)*(X(1)-X(NN))/(Y(NN)-Y(1))
      Y(1)=0.
    2 CONTINUE
      DX=X(NN)-X(1)
      DY=Y(NN)-Y(1)
      DO 1 I=2,NN
      TEMP=FLOAT(I-1)*RFN
      X(I)=X(1)+TEMP*DX
    1 Y(I)=Y(1)+TEMP*DY
      RETURN
      END
$      FORTRAN
CPREGH
      SUBROUTINE PREGH
      DIMENSION T(3,3),C(3,3),B(3,3)
      COMMON/PREGHC/T,DELTX,DELTY,DELTZ
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      C(1,1)=CG*CE
      C(1,2)=CG*SE
```

```
      C(1,3)=-SG
      C(2,1)=-SE
      C(2,2)=CE
      C(2,3)=0.
      C(3,1)=SG*CE
      C(3,2)=SG*SE
      C(3,3)=CG
      B(1,1)=CT*CA
      B(1,2)=CT*SA
      B(1,3)=-ST
      B(2,1)=SP*ST*CA-CP*SA
      B(2,2)=SP*ST*SA+CP*CA
      B(2,3)=SP*CT
      B(3,1)=CP*ST*CA+SP*SA
      B(3,2)=CP*ST*SA-SP*CA
      B(3,3)=CP*CT
      DO 1 I=1,3
      DO 1 J=1,3
      S=0.
      DO 2 K=1,3
    2 S=S+C(I,K)*B(K,J)
    1 T(I,J)=S
      DELTX=C(1,1)*D8 +C(1,2)*D9 +C(1,3)*D10
      DELTY=C(2,1)*D8 +C(2,2)*D9 +C(2,3)*D10
      DELTZ=C(3,1)*D8 +C(3,2)*D9 +C(3,3)*D10
      RETURN
      END
$      FORTRAN
CGH
      SUBROUTINE GH(X,Y,Z,G,H)
      DIMENSION T(3,3)
      COMMON/PREGHC/T,DELTX,DELTY,DELTZ
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      ZA=Z+D1
      XD=T(1,1)*X +T(1,2)*Y +T(1,3)*ZA +DELTX
      YD=T(2,1)*X +T(2,2)*Y +T(2,3)*ZA +DELTY
      ZD=T(3,1)*X +T(3,2)*Y +T(3,3)*ZA +DELTZ
      G=RSCF*D11*YD/XD
      H=.5*RVPICS-RSCF*D11*ZD/XD
      RETURN
      END
$      EXECUTE
$      LIMITS  30,38000,,15000
19.         -5.         1.5
14.         -4.         1.2
20.         .5          .35
20.         -.5         .35
27.         11.         8.
23.         -5.         .6
28.         1.          1.
25.5        0.          .5
29.         -2.         .5
17.         -20.        10.
15.         6.          .5
8.          -1.         .1
```

9.	0.	.1	
11.	0.	.1	
11.	-1.	.1	
12.	4.	.1	
13.	6.	.1	
15.	-1.	.2	
15.	2.	.2	
16.	9.	.1	
17.	3.	.2	
17.	6.	.1	
19.	-3.	.2	
19.	4.	.1	
18.	-1.	.1	
18.	1.	.2	
20.	3.	.1	
21.	-3.	.1	
21.	-2.	.1	
22.	-3.	.2	
22.	4.	.2	
23.	3.	.1	
24.	-3.	.1	
24.	2.	.1	
25.	2.	.2	
26.	-6.	.2	
26.	-4.	.2	
27.	-4.	.1	
27.	-2.	.1	
28.	-5.	.1	
29.	-7.	.2	
30.	-4.	.2	
31.	-5.	.1	
31.	-7.	.2	
13.	0.	.2	
14.	0.	.2	
14.	1.	.2	
14.	2.	.2	
15.	1.	.2	
+1.	.111	1	0.50
-5.	2.	1	0.50
-1.	.1	1	0.75
-4.	1.	1	0.75
-2.	.125	1	1.00
-3.	2.	1	1.00
0.	.125	1	1.25
-4.	4.	1	1.25
0.	.1	1	1.50
-4.	3.	1	1.50
-5.	.125	1	1.75
-2.	2.	1	1.75
0.	.1	1	2.00
0.	1.	1	2.00
0.	.1	1	2.25
2.	0.	1	2.25
0.	.167	1	2.50
5.	-1.	1	2.50
-5.	.125	1	2.75
6.	0.	1	2.75

0.	.125	1	3.00
8.	2.	1	3.00
-2.	.1	1	3.25
9.	4.	1	3.25
-3.	.167	1	3.50
10.	5.	1	3.50
-3.	.125	1	3.75
8.	3.	1	3.75
0.	.1	1	4.00
7.	1.	1	4.00
+1.	.167	1	4.25
3.	1.	1	4.25
0.	.167	1	4.50
2.	-5.	1	4.50
+5.	.143	1	4.75
0.	-4.	1	4.75
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	-10.	1	
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
+2.	.125	1	5.25
+1.	-2.	1	5.25
0.	.125		
+1.	.125	1	5.50
0.	0.	1	5.50
0.	.125		
+3.	.125	1	5.75
1.	1.	1	5.75
0.	.125		
0.	-10.	1	
0.	.111	1	6.00
2.	2.	1	6.00
0.	.125		
0.			

-4.	.125	1	6.25
1.	3.	1	6.25
0.	.125		
0.	.125	1	6.50
0.	5.	1	6.50
0.	.125		
0.	.111	1	6.75
-2.	6.	1	6.75
0.	.125		
0.	-10.	1	
+2.	.1	1	7.00
-4.	7.	1	7.00
0.	.125		
-20.			
-5.	.125	1	7.25
-4.	8.	1	7.25
0.	.125		
+2.	.125	1	7.50
-5.	10.	1	7.50
0.	.125		
+1.	.167	1	7.75
-7.	11.	1	7.75
0.	.125		
0.	-10.	1	
-5.	.167	1	8.00
-9.	12.	1	8.00
28.	.125		
28.			
-3.	.2	1	8.25
-7.	13.	1	8.25
28.	.125		
-6.	.125	1	8.50
-5.	10.	1	8.50
28.	.125		
-1.	.167	1	8.75
-3.	8.	1	8.75
28.	.125		
0.	.125	1	9.00
-1.	6.	1	9.00
28.	.125		
-4.	.1	1	9.25
-1.	4.	1	9.25
28.	.125		
0.	.1	1	9.50
0.	-1.	1	9.50
28.	.125		
0.	.125	1	9.75
1.	-2.	1	9.75
28.	.125		
0.	-10.	1	
0.	.125	1	10.00
3.	-3.	1	10.00
28.	.125		
0.			
-1.	.143	1	10.25
5.	-2.	1	10.25
28.	.125		

).	.167	1	10.50
2.	-2.	1	10.50
28.	.125		
+1.	.125	1	10.75
).	0.	1	10.75
28.	.125		
+1.	.125	1	11.00
1.	2.	1	11.00
28.	.125		
).	.143	1	11.25
2.	3.	1	11.25
28.	.125		
-1.	.125	1	11.50
3.	3.	1	11.50
28.	.125		
-2.	.167	1	11.75
4.	4.	1	11.75
28.	.125		
).	-10.	1	
+5.	.2	1	12.00
5.	4.	1	12.00
28.	.125		
).			
-3.	.143	1	12.25
4.	3.	1	12.25
28.	.125		
-1.	.125	1	12.50
3.	3.	1	12.50
28.	.125		
).	.143	1	12.75
4.	4.	1	12.75
28.	.125		
+1.	.111	1	13.00
5.	4.	1	13.00
28.	.125		
+2.	.125	1	13.25
7.	5.	1	13.25
28.	.125		
+5.	.125	1	13.50
).	5.	1	13.50
28.	.125		
-15.	.111	1	13.75
4.	4.	1	13.75
28.	.125		
).	-10.	1	
-28.	.111	1	14.00
1.	4.	1	14.00
28.	.125		
).			
-29.	.125	1	14.25
).	3.	1	14.25
28.	.125		
-27.	.167	1	14.50
-1.	3.	1	14.50
28.	.125		
-28.	.111	1	14.75
-3.	2.	1	14.75

28.	.125		
+28.	.111	1	15.00
-5.	2.	1	15.00
28.	.125		
27.	.143	1	15.25
-7.	-1.	1	15.25
28.	.125		
28.	.143	1	15.50
-6.	-1.	1	15.50
28.	.125		
29.	.125	1	15.75
-5.	0.	1	15.75
28.	.125		
0.	-10.	1	
27.	.125	1	16.00
-4.	0.	1	16.00
28.	.125		
0.			
26.	.143	1	16.25
-3.	1.	1	16.25
28.	.125		
26.	.125	1	16.50
-2.	1.	1	16.50
28.	.125		
28.	.143	1	16.75
-1.	2.	1	16.75
28.	.125		
29.	.167	1	17.00
0.	2.	1	17.00
28.	.125		
27.	.125	1	17.25
0.	3.	1	17.25
28.	.125		
28.	.111	1	17.50
1.	3.	1	17.50
28.	.125		
28.	.1	1	17.75
1.	2.	1	17.75
28.	.125		
0.	-10.	1	
29.	.125	1	18.00
2.	2.	1	18.00
28.	.125		
0.			
28.	.125	1	18.25
3.	3.	1	18.25
28.	.125		
28.	.143	1	18.50
-2.	2.	1	18.50
28.	.125		
28.	.125	1	18.75
-1.	1.	1	18.75
28.	.125		
28.	.167	1	19.00
-2.	3.	1	19.00
28.	.125		
25.	.125	1	19.25

-2.	4.	1	19.25
28.	.125		
27.	.125	1	19.50
-3.	4.	1	19.50
28.	.125		
26.	.125	1	19.75
-2.	5.	1	19.75
28.	.125		
0.	-10.	1	
30.	.125	1	20.00
0.	4.	1	20.00
28.	.125		
0.			
30.	.143	1	20.25
1.	6.	1	20.25
28.	.125		
29.	.167	1	20.50
2.	7.	1	20.50
28.	.125		
26.	.143	1	20.75
3.	7.	1	20.75
28.	.125		
27.	.125	1	21.00
3.	3.	1	21.00
28.	.125		
26.	.143	1	21.25
4.	4.	1	21.25
28.	.125		
25.	.143	1	21.50
4.	4.	1	21.50
28.	.125		
28.	.143	1	21.75
3.	3.	1	21.75
28.	.125		
0.	-10.	1	
29.	.167	1	22.00
3.	7.	1	22.00
28.	.125		
0.			
30.	.167	1	22.25
2.	6.	1	22.25
28.	.125		
28.	.143	1	22.50
2.	4.	1	22.50
28.	.125		
29.	.143	1	22.75
1.	3.	1	22.75
28.	.125		
28.	.125	1	23.00
0.	2.	1	23.00
28.	.125		
29.	.125	1	23.25
0.	1.	1	23.25
28.	.125		
28.	.125	1	23.50
1.	1.	1	23.50
28.	.125		

```
28.        .125      1                                      23.75
0.         0.        1                                      23.75
28.        .125
$      ENDJOB
```

```
$      IDENT    366,52120,2064B,65054,COX
$      OPTION   FORTRAN
$      FORTRAN
       DIMENSION VRT(200),VPT(200),IVBTP(200),CAZT(200),CELT(200),ICAMTP(
      1200),CAZC(200),CELC(200),HC(200),VC(200),X(200),Y(200),Z(200),
      2DELX(200),DELY(200),DELZ(200),YT(200),VT(200),ITP(200),
      3                          RJSHA(200),FWLSX(11),FWLSY(11), FWRSX(11),
      4FWRSY(11),RMWLSX(11),RMWLSY(11),RMWRSX(11),RMWRSY(11),POPLX(11),
      5POPLY(11),POPRX(11),POPRY(11),GLP10X(11),GLP10Y(11),GLP20X(11),
      6GLP20Y(11),GLM10X(11),GLM10Y(11),GLM20X(11),GLM20Y(11),PRPLX(200),
      7PRPLY(200),PRPRX(200),PRPRY(200),        R(7),        GCRTX(7),GCRTY(7
      8),GCX(7, 61),GCY(7, 61)
      A                        ,RJSPLX(11),RJSPLY(11),RJSPRX(11),RJSPRY(11)
       COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
      1,CA,SA
       COMMON/PLTCOM/RHPICS,RVPICS,RSCF
       COMMON/LINCOM/X1,Y1,Z1,X2,Y2,NN
       DO 11 I=1,22
       YT(I)=0.
       VT(I)=.125
       ITP(I)=1
       VRT(I)=0.
       VPT(I)=0.
       IVBTP(I)=1
       CAZT(I)=0.
       CELT(I)=-10.
       ICAMTP(I)=1
       RJSHA(I)=0.
    11 CONTINUE
       DO 20 I=23,40
       RJSHA(I)=0.
    20 CONTINUE
       NN=11
       PDLY=6.
       TMDLY=1.3
       CMDLY=4.
       TMR=4.
       D1=.3
       D2=.611
       D3=.733
       D4=.203
       D5=.685
       D6=.457
       D7=.882
       D8=0.
       D9=0.
       D10=1.7
       D11=.1015
       GCRTX(6)=D8+D11
       GCRTY(6)=D9
       GCRTX(7)=D8+D11
       GCRTY(7)=D9
       HFOV=60.
       VFOV=40.
       RA=1.
       CS=.7
       DTR=.0174533
```

```
      TERM10=1.*DTR
      RVPICS=.254
      RSCF=RVPICS/(2.*D11*TAN(.5*VFOV*DTR) )
      RHPICS=RSCF*2.*D11*TAN(.5*HFOV*DTR)
      RTMR=1./TMR
      R(1)=5.
      R(2)=10.
      R(3)=30.
      R(4)=100.
      R(5)=0.
      QRA=TAN(RA*DTR)
C******** ATEM*R(6)**2 + BTEM*R(6) + CTEM = 0
      ATEM=QRA
      BTEM=CS*QRA
      CTEM=(D1+D10)*((D1+D10)*QRA-CS)
      R(6)=(-BTEM+SQRT(BTEM**2 -4.*ATEM*CTEM) )/(2.*ATEM)
      R(7)=R(6)+CS
C******** ROUND DOWN FOR ISPTM, ROUND UP FOR ISPC
      ISPTM=TMR*(PDLY-TMDLY)+.001
      ISPC=TMR*(PDLY+CMDLY)+.999
      ISPCP1=ISPC+1
      D1D10S=(D1+D10)**2
      SINHFV=SIN(.5*HFOV*DTR)
      ILPR=0
      DO 955 IJ=1,100
      IPR=41
      X(1)=0.
      Y(1)=0.
      Z(1)=0.
      IL1=IPR-ILPR
      ILPR=IPR
      IF(IL1.GT.  ISPC)GO TO 100
      DO 53 J=2,ISPCP1
      JPIL1=J+IL1
      DELX(J)=DELX(JPIL1)
      DELY(J)=DELY(JPIL1)
      DELZ(J)=DELZ(JPIL1)
   53 CONTINUE
      GO TO 550
  100 DO 501 J=2,ISPCP1
      IT=IPR-ISPTM +J-2
      IF(IT.GE.IPR)GO TO 230
      READ(5,2)YT(IT),VT(IT),ITP(IT)
    2 FORMAT(2E12.0,I2)
      IF(ITP(IT).LT.1)GO TO 230
      READ(5,2)VRT(IT),VPT(IT),IVBTP(IT)
  150 PVH=YT(IT)
      PVV=VT(IT)
      PVP=VPT(IT)
      GO TO 400
  230 IT21=IPR-ISPC +J-2
      READ(5,2)HC(IT21),VC(IT21)
      PVH=HC(IT21)
      PVV=VC(IT21)
      PVP=0.
  400 TEMP1=RTMR*PVV
      TEMP2=PVH*DTR
```

```
      DELX(J)=TEMP1*COS(TEMP2)
      DELY(J)=TEMP1*SIN(TEMP2)
      DELZ(J)=-DELX(J)*TAN(PVP*DTR)
      IF(IT.GT.IPR-1)GO TO 501
501   CONTINUE
550   CONTINUE
      DO 301 J=1,4
      IS3=IPR-ISPTM +J-1
      IF(IVBTP(IS3).EQ.1)GO TO 320
301   CONTINUE
      GO TO 340
320   VR=VRT(IS3)
      VP=VPT(IS3)
      VY=YT(IS3)
      GO TO 360
340   VR=0.
      VP=0.
      ITEM1=IPR-ISPC
      VY=HC(ITEM1)
360   ITEM=IPR-ISPTM
      READ(5,2)CAZT(ITEM),CELT(ITEM),ICAMTP(ITEM)
      IF(ICAMTP(ITEM).LT.1)GO TO 450
      CEL=CELT(ITEM)
      CAZ=CAZT(ITEM)
      GO TO 500
450   ITEM1=IPR-ISPC
      READ(5,2)CAZC(ITEM1),CELC(ITEM1)
      CEL=CELC(ITEM1)
      CAZ=CAZC(ITEM1)
500   TEM=VP*DTR
      CT=COS(TEM)
      ST=SIN(TEM)
      TEM=VP*DTR
      CP=COS(TEM)
      SP=SIN(TEM)
      TEM=CAZ*DTR
      CE=COS(TEM)
      SE=SIN(TEM)
      TEM=CEL*DTR
      CG=COS(TEM)
      SG=SIN(TEM)
      KK=0
      ICL=IPR
      ITA=ICL-IPR
      ITAP42= ITA +ISPC+2
      ITAP21= ITA +ISPTM+2
      READ(5,2)YT(ICL),VT(ICL),ITP(ICL)
      IF(ITP(ICL).LT.1)GO TO 220
      READ(5,2)VRT(ICL),VPT(ICL),IVBTP(ICL)
      IF(IVBTP(ICL).LT.1)GO TO 220
      PVH=YT(ICL)
      PVV=VT(ICL)
      PVP=VPT(ICL)
      TEMP1=RTMR*PVV
      TEMP2=PVH*DTR
      DELX(ITAP21)=TEMP1*COS(TEMP2)
      DELY(ITAP21)=TEMP1*SIN(TEMP2)
```

```
      DELZ(ITAP21)=-DELX(ITAP21)*TAN(PVP*DTR)
  220 READ(5,2)HC(ICL),VC(ICL)
      PVH=HC(ICL)
      PVV=VC(ICL)
      PVP=0.
      TEMP1=RTMR*PVV
      TEMP2=PVH*DTR
      DELX(ITAP42)=TEMP1*COS(TEMP2)
      DELY(ITAP42)=TEMP1*SIN(TEMP2)
      DELZ(ITAP42)=0.
      IF(ICL.GT.IPR)GO TO 300
      GO TO 410
  300 IF(8*(KK/8).NE.KK)GO TO 35
  410 DO 451 J=2,ITAP42
      X(J)=DELX(J)+X(J-1)
      Y(J)=DELY(J)+Y(J-1)
  451 Z(J)=DELZ(J)+Z(J-1)
      X1OPTA=X(ITAP42)
      Y1OPTA=Y(ITAP42)
      Z1OPTA=Z(ITAP42)
      READ(5,2)RJSHA(ICL)
      RJSH=RJSHA(ICL)
      TEMP1=X1OPTA+D3
      TEMP6=Y1OPTA-.5*D2
      TEMP7=Y1OPTA+.5*D2
      TEMP8=Y1OPTA-.5*D4
      CA=1.
      SA=0.
      CALL PREGH
      X1=TEMP1
      Y1=TEMP6
      Z1=Z1OPTA
      X2=TEMP1+2300.*COS(RJSH*DTR)
      Y2=Y1+2300.*SIN(RJSH*DTR)
      CALL LINE(RJSPLX,RJSPLY)
      Y1=TEMP7
      Y2=Y2+D2
      CALL LINE(RJSPRX,RJSPRY)
      TEM2=VY*DTR
      CA=COS(TEM2)
      SA=SIN(TEM2)
      CALL PREGH
      X2=TEMP1
      Y1=TEMP8-.5*D2
      Y2=Y1+D4
      CALL LINE(FWLSX,FWLSY)
      Y1=Y1+D2
      Y2=Y2+D2
      CALL LINE(FWRSX,FWRSY)
      X1=X1-D5
      X2=X1
      Y1=Y1-D2
      Y2=Y2-D2
      CALL LINE(RMWLSX,RMWLSY)
      Y1=Y1+D2
      Y2=Y2+D2
      CALL LINE(RMWRSX,RMWRSY)
```

```
      IL5=ITAP21
      IF(ITA.EQ.0)IL5=1
      DO 302 I=IL5,ITAP42
      TEMP1=D3+X(I)
      CALL GH(TEMP1,Y(I)-.5*D2,Z(I),PRPLX(I),PRPLY(I))
      CALL GH(TEMP1,Y(I)+.5*D2,Z(I),PRPRX(I),PRPRY(I))
  302 CONTINUE
      TEMP1=X1OPTA+D3
      X1=TEMP1
      X2=TEMP1+2300.*COS(HC(ICL)*DTR)
      Y1=TEMP6
      Y2=TEMP6+2300.*SIN(HC(ICL)*DTR)
      CALL LINE(POPLX,POPLY)
      Y1=TEMP7
      Y2=Y2+D2
      CALL LINE(POPRX,POPRY)
      X1=TEMP1
      TEM1=(HC(ICL)+10.)*DTR
      TEM2=TEM1-20.*DTR
      X2=X1+2300.*COS(TEM1)
      Y1=Y1OPTA
      Y2=Y1+2300.*SIN(TEM1)
      CALL LINE(GLP10X,GLP10Y)
      X2=X1+2300.*COS(TEM2)
      Y2=Y1+2300.*SIN(TEM2)
      CALL LINE(GLM10X,GLM10Y)
      TEM1=(HC(ICL)+20.)*DTR
      TEM2=TEM1-40.*DTR
      X2=X1+2300.*COS(TEM1)
      Y2=Y1+2300.*SIN(TEM1)
      CALL LINE(GLP20X,GLP20Y)
      X2=X1+2300.*COS(TEM2)
      Y2=Y1+2300.*SIN(TEM2)
      CALL LINE(GLM20X,GLM20Y)
      DO 31 I=1,5
      GCRTX(I)=TEMP1
      GCRTY(I)=Y1OPTA
   31 CONTINUE
      TERM9=DTR*(60.-HC(ICL))
      DO 30 J=1,61
      TERM1=TERM9+TERM10*FLOAT(J-1)
      TERM2=SIN(TERM1)
      TERM3=COS(TERM1)
      DO 30 I=1,7
      IF(R(I).LT.1.E-6)GO TO 30
      TEMP=Z1OPTA
      IF(I.GT.5)TEMP=0.
      CALL GH(GCRTX(I)+R(I)*TERM2,GCRTY(I)+R(I)*TERM3,TEMP,GCX(I,J),
     1GCY(I,J))
   30 CONTINUE
   35 KK=KK+1
      IF(IJ.GT.95)WRITE(6,696)IJ
  696 FORMAT(1H ,3X,I6)
  955 CONTINUE
      STOP
      END
$       FORTRAN
```

```
CLINE
      SUBROUTINE LINE(X,Y)
      DIMENSION X(1),Y(1)
      COMMON/LINCOM/X1,Y1,Z1,X2,Y2,NN
      RFN=1./FLOAT(NN-1)
      CALL GH(X1,Y1,Z1,X(1),Y(1))
      CALL GH(X2,Y2,Z1,X(NN),Y(NN))
      IF(Y(1).GE.0.)GO TO 2
      IF(Y(NN).LE.0.)GO TO 2
      X(1)=X(1)+Y(1)*(X(1)-X(NN))/(Y(NN)-Y(1))
      Y(1)=0.
    2 CONTINUE
      DX=X(NN)-X(1)
      DY=Y(NN)-Y(1)
      DO 1 I=2,NN
      TEMP=FLOAT(I-1)*RFN
      X(I)=X(1)+TEMP*DX
    1 Y(I)=Y(1)+TEMP*DY
      RETURN
      END
$      FORTRAN
CPREGH
      SUBROUTINE PREGH
      DIMENSION T(3,3),C(3,3),B(3,3)
      COMMON/PREGHC/T,DELTX,DELTY,DELTZ
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      C(1,1)=CG*CE
      C(1,2)=CG*SE
      C(1,3)=-SG
      C(2,1)=-SE
      C(2,2)=CE
      C(2,3)=0.
      C(3,1)=SG*CE
      C(3,2)=SG*SE
      C(3,3)=CG
      B(1,1)=CT*CA
      B(1,2)=CT*SA
      B(1,3)=-ST
      B(2,1)=SP*ST*CA-CP*SA
      B(2,2)=SP*ST*SA+CP*CA
      B(2,3)=SP*CT
      B(3,1)=CP*ST*CA+SP*SA
      B(3,2)=CP*ST*SA-SP*CA
      B(3,3)=CP*CT
      DO 1 I=1,3
      DO 1 J=1,3
      S=0.
      DO 2 K=1,3
    2 S=S+C(I,K)*B(K,J)
    1 T(I,J)=S
      DELTX=C(1,1)*D8 +C(1,2)*D9 +C(1,3)*D10
      DELTY=C(2,1)*D8 +C(2,2)*D9 +C(2,3)*D10
      DELTZ=C(3,1)*D8 +C(3,2)*D9 +C(3,3)*D10
      RETURN
      END
$      FORTRAN
```

```
CGH
      SUBROUTINE GH(X,Y,Z,G,H)
      DIMENSION T(3,3)
      COMMON/PREGHC/T,DELTX,DELTY,DELTZ
      COMMON/GHCOM/ST,CT,SP,CP,SE,CE,SG,CG,D1,D8,D9,D10,D11,XD,YD,ZD
     1,CA,SA
      COMMON/PLTCOM/RHPICS,RVPICS,RSCF
      ZA=Z+D1
      XD=T(1,1)*X +T(1,2)*Y +T(1,3)*ZA +DELTX
      YD=T(2,1)*X +T(2,2)*Y +T(2,3)*ZA +DELTY
      ZD=T(3,1)*X +T(3,2)*Y +T(3,3)*ZA +DELTZ
      G=RSCF*D11*YD/XD
      H=.5*RVPICS-RSCF*D11*ZD/XD
      RETURN
      END
$       EXECUTE
$       LIMITS  30,38000,,15000
+1.         .111          1                                          0.50
-5.         2.            1                                          0.50
-1.         .1            1                                          0.75
-4.         1.            1                                          0.75
-2.         .125          1                                          1.00
-3.         2.            1                                          1.00
0.          .125          1                                          1.25
-4.         4.            1                                          1.25
0.          .1            1                                          1.50
-4.         3.            1                                          1.50
-5.         .125          1                                          1.75
-2.         2.            1                                          1.75
0.          .1            1                                          2.00
0.          1.            1                                          2.00
0.          .1            1                                          2.25
2.          0.            1                                          2.25
0.          .167          1                                          2.50
5.          -1.           1                                          2.50
-5.         .125          1                                          2.75
6.          0.            1                                          2.75
0.          .125          1                                          3.00
8.          2.            1                                          3.00
-2.         .1            1                                          3.25
9.          4.            1                                          3.25
-3.         .167          1                                          3.50
10.         5.            1                                          3.50
-3.         .125          1                                          3.75
8.          3.            1                                          3.75
0.          .1            1                                          4.00
7.          1.            1                                          4.00
+1.         .167          1                                          4.25
3.          1.            1                                          4.25
0.          .167          1                                          4.50
2.          -5.           1                                          4.50
+5.         .143          1                                          4.75
0.          -4.           1                                          4.75
0.          .125
0.          .125
0.          .125
0.          .125
0.          .125
0.          .125
0.          .125
0.          .125
```

0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	.125		
0.	-10.	1	
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00

.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		

0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			

-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00

-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
).	.125		
).			
-5.	.143	1	5.00
-2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00
.	.125		
.			
5.	.143	1	5.00
2.	-3.	1	5.00

0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		

0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			
-5.	.143	1	5.00
-2.	-3.	1	5.00
0.	.125		
0.			

```
-5.        .143      1                                                        5.00
-2.        -3.       1                                                        5.00
0.         .125
0.
-5.        .143      1                                                        5.00
-2.        -3.       1                                                        5.00
0.         .125
0.
-5.        .143      1                                                        5.00
-2.        -3.       1                                                        5.00
0.         .125
0.
-5.        .143      1                                                        5.00
-2.        -3.       1                                                        5.00
0.         .125
0.
$      ENDJOB
```

APPENDIX F: TELEMETRY AND COMMAND VALUES VERSUS TIME FOR USE IN TRAVERSAL THROUGH THE CRATER FIELD TEST CASE OF REMOTE DRIVING AIDS COMPUTER PROGRAM

TIME (seconds) t =	VEHICLE ROLL TM (degrees)	VEHICLE PITCH TM (degrees)	VEHICLE YAW TM (degrees)	HEADING COMMANDS (degrees relative to due East)	VELOCITY TM (km/hr)	VELOCITY COMMANDS (km/hr)	JOYSTICK HEADING (degrees relative to instantaneous vehicle heading)	CAMERA ELEVATION COMMANDS ∉ TM (degrees relative to horizontal-line-of-sight)	CAMERA AZIMUTH COMMANDS ∉ TM (degrees relative to instantaneous vehicle heading)
88.5	-5.0	2.0	1.0	0.	0.111	0.125	0	-10.0	0.
88.7	-4.0	1.0	-1.0		0.100				0.
89.0	-3.0	2.0	-2.0		0.125				0.
89.2	-4.0	4.0	0.		0.125				0.
89.5	-4.0	3.0	0.		0.100				0.
89.7	-2.0	2.0	-5.0		0.125				0.
90.0	0.	1.0	0.		0.100				0.
90.2	2.0	0.	0.		0.100				0.
90.5	5.0	-1.0	0.		0.167				0.
90.7	6.0	0.	-5.0		0.125				0.
91.0	8.0	2.0	0.		0.125				0.
91.2	9.0	4.0	-2.0		0.100				0.
91.5	10.0	5.0	-3.0		0.167				0.
91.7	8.0	3.0	-3.0		0.125				0.
92.0	7.0	1.0	0.		0.100				0.
92.2	3.0	1.0	1.0		0.167				0.
92.5	2.0	-5.0	0.		0.167				0.

TIME (seconds) t =	ROLL TM (degrees)	PITCH TM (degrees)	YAW TM (degrees)	HEADING COMMANDS (degrees)	VELOCITY TM (km/hr)	VELOCITY COMMANDS (km/hr)	JOYSTICK HEADING (degrees)	CAMERA ELEVATION COMMANDS ∉ TM (degrees)	CAMERA AZIMUTH COMMANDS ∉ TM (degrees)
92.7	0.	-4.0	5.0	0.	0.143	0.125	0.0	-10.0	0.
93.0	-2.0	-3.0	-5.0		0.143				0.
93.2	-1.0	-2.0	2.0		0.175				0.
93.5	0.	0.	1.0		0.125				0.
93.7	1.0	1.0	3.0		0.125				0.
94.0	2.0	2.0	0.		0.111				0.
94.2	1.0	3.0	-4.0		0.125				0.
94.5	0.	5.0	0.		0.125				0.
94.7	-2.0	6.0	0.		0.111				0.
95.0	-4.0	7.0	2.0		0.100		-20.0		0.
95.2	-4.0	8.0	-5.0		0.125				0.
95.5	-5.0	10.0	2.0		0.125				0.
95.7	-7.0	11.0	1.0		0.167				0.
96.0	-9.0	12.0	-5.0	+28.0	0.167		+28.0		0.
96.2	-7.0	13.0	-3.0		0.200				0.
96.5	-5.0	10.0	-6.0		0.125				0.
96.7	-3.0	8.0	-1.0		0.167				0.
97.0	-1.0	6.0	0.		0.125				0.
97.2	-1.0	4.0	-4.0		0.100				0.
97.5	0.	-1.0	0.		0.100				0.
97.7	1.0	-2.0	0.		0.125				0.
98.0	3.0	-3.0	0.		0.125				0.
98.2	5.0	-2.0	-1.0		0.143				0.

APPENDIX F (CONT'D)

TIME (seconds) t =	ROLL TM (degrees)	PITCH TM (degrees)	YAW TM (degrees)	HEADING COMMANDS (degrees)	VELOCITY TM (km/hr)	VELOCITY COMMANDS (km/hr)	JOYSTICK HEADING (degrees)	CAMERA ELEVATION COMMANDS ℄ TM (degrees)	CAMERA AZIMUTH COMMANDS ℄ TM (degrees)
98.5	2.0	-2.0	0.	+28.0	0.167	0.125	+28.0	-10.0	0.
98.7	0.	0.	1.0		0.125				0.
99.0	1.0	2.0	1.0		0.125				0.
99.2	2.0	3.0	0.		0.143				0.
99.5	3.0	3.0	-1.0		0.125				0.
99.7	4.0	4.0	-2.0		0.167				0.
100.0	5.0	4.0	5.0		0.200				0.
100.2	4.0	3.0	-3.0		0.143				0.
100.5	3.0	3.0	-1.0		0.125				0.
100.7	4.0	4.0	0.		0.143				0.
101.0	5.0	4.0	1.0		0.111				0.
101.2	7.0	5.0	2.0		0.125				0.
101.5	6.0	5.0	5.0		0.125				0.
101.7	4.0	4.0	15.0		0.111				0.
102.0	1.0	4.0	28.0		0.111				0.
102.2	0.	3.0	29.0		0.125				0.
102.5	-1.0	3.0	27.0		0.167				0.
102.7	-3.0	2.0	28.0		0.111				0.
103.0	-5.0	2.0	28.0		0.111				0.
103.2	-7.0	-1.0	27.0		0.143				0.
103.5	-6.0	-1.0	28.0		0.143				0.

APPENDIX F (CONT'D)

TIME (seconds) t =	ROLL TM (degrees)	PITCH TM (degrees)	YAW TM (degrees)	HEADING COMMANDS (degrees)	VELOCITY TM (km/hr)	VELOCITY COMMANDS (km/hr)	JOYSTICK HEADING (degrees)	CAMERA ELEVATION COMMANDS ∉ TM (degrees)	CAMERA AZIMUTH COMMANDS ∉ TM (degrees)
103.7	-5.0	0.	29.0	+28.0	0.125	0.125	+28.0	-10.0	0.
104.0	-4.0	0.	27.0		0.125				0.
104.2	-3.0	1.0	26.0		0.143				0.
104.5	-2.0	1.0	26.0		0.125				0.
104.7	-1.0	2.0	28.0		0.143				0.
105.0	0.	2.0	29.0		0.167				0.
105.2	0.	3.0	27.0		0.125				0.
105.5	1.0	3.0	28.0		0.111				0.
105.7	1.0	2.0	28.0		0.100				0.
106.0	2.0	2.0	29.0		0.125				0.
106.2	3.0	3.0	28.0		0.125				0.
106.5	-2.0	2.0	28.0		0.143				0.
106.7	-1.0	1.0	28.0		0.125				0.
107.0	-2.0	3.0	28.0		0.167				0.
107.2	-2.0	4.0	25.0		0.125				0.
107.5	-3.0	4.0	27.0		0.125				0.
107.7	-2.0	5.0	26.0		0.125				0.
108.0	0.	4.0	30.0		0.125				0.
108.2	1.0	6.0	30.0		0.143				0.

APPENDIX F (CONT'D)

TIME (seconds) t =	ROLL TM (degrees)	PITCH TM (degrees)	YAW TM (degrees)	HEADING COMMANDS (degrees)	VELOCITY TM (km/hr)	VELOCITY COMMANDS (km/hr)	JOYSTICK HEADING (degrees)	CAMERA ELEVATION COMMANDS ¢ TM (degrees)	CAMERA AZIMUTH COMMANDS ¢ TM (degrees)
108.5	2.0	7.0	29.0	+28.0	0.167	0.125	+28.0	-10.0	0.
108.7	3.0	7.0	26.0		0.143				0.
109.0	3.0	3.0	27.0		0.125				0.
109.2	4.0	4.0	26.0		0.143				0.
109.5	4.0	4.0	25.0		0.143				0.
109.7	3.0	3.0	28.0		0.143				0.
110.0	3.0	7.0	29.0		0.167				0.
110.2	2.0	6.0	30.0		0.167				0.
110.5	2.0	4.0	28.0		0.143				0.
110.7	1.0	3.0	29.0		0.143				0.
111.0	0.	2.0	28.0		0.125				0.
111.2	0.	1.0	29.0		0.125				0.
111.5	1.0	1.0	28.0		0.125				0.
111.7	0.	0.	28.0		0.125				0.

APPENDIX G. Computer Programs Listings (FORTRAN IV Language) for the Three Cases Applying to the JPL Vehicle. Case 1 Program Listing is as follows:

```
$       IDENT   366,52120,2064B,72097,FILETTI
$       OPTION  FORTRAN
$       FORTRAN
      DIMENSION FWLSX(10),FWRSX(10),WMLSX(10),WMRSX(10),FWFX(10),
     1 RFFX(10),FBX(10),PPLX(182),PPLY(182),PPRX(182),PPRY(182),
     2 GLP10X(182),GLP10Y(182),GLP20X(182),GLM10X(182),GLM20X(182),
     3 GCTX(182),GCTY(182),GCHX(182),GCHY(182),GCTHX(182),GCTHY(182),
     4 CH1X(182),CH1Y(182),CH2X(182),CH2Y(182)     ,
     5 FWSY(10),WMSY(10),FWFY(10),FBY(10)
   33 REAL N
   35 D(X,Z)=(C*X)+(S*Z)+(34.*S)
   40 N(X,Z)=(-S*X)+(C*Z)+(34.*C)
   45 A(X,Y,Z)=(8.20*4.*(Y/(D(X,Z)))  )
   50 B(X,Z)=6.7-(8.20*4.*(N(X,Z))/(D(X,Z)))
   55 X3(R,X)=156.7+(R*(SIN((X-1.)*P)))
   60 X4(R,X)=(R*(SIN((X    )*P)))+4.
   65 Y2(Q)=(X2)*(TAN(Q*P))
   70 Y3(R,X)=R*(COS((X-1.)*P))
   75 P=3.14159265/180.
   80 C=COS(5.*P)
   85 S=SIN(5.*P)
   90 DO 250 I=1,9
   95 RI=I
  100 FBY(I)=B(154.2,-7.75)
  105 FWSY(I)=B(147.7,0.)
  110 WMSY(I)=B(120.7,0.)
  120 FWFY(I)=B(156.7,-9.)
  130 FWLSX(I)=A(147.7,(-17.+RI),0.)
  140 FWRSX(I)=A(147.7,7.+RI,0.)
  150 WMLSX(I)=A(120.7,-17.+RI,0.)
  160 WMRSX(I)=A(120.7,7.+RI,0.)
  170 FWFX(I)=A(156.7,-17.+RI,-9.)
  180 RFFX(I)=A(156.7,7.+RI,-9.)
  190 FBX(I)=A(154.2,(-6.75+(1.6875*((RI)-1.))),-7.75)
  200 WRITE(6,210)FWLSX(I),FWRSX(I),FWSY(I),WMLSX(I),WMRSX(I),WMSY(I)  ,
  2051 FWFX(I),RFFX(I),FWFY(I),FBX(I),FBY(I)
  210 FORMAT(/,12E10.3)
 250  CONTINUE
  260 DO 500 J=1,181
  270 RJ=J
  280 X5=156.7+((RJ)-1.)*(1.2**(RJ))
  290 PPLX(J)=A(X5,-12.,0.)
  300 PPLY(J)=B(X5,0.)
  310 PPRX(J)=A(X5,12.,0.)
  320 X2=156.7+((RJ)-1.)*(1.2**(RJ))
  330 GLP10X(J)=A((X2),Y2(10.),0.)
  340 GLP10Y(J)=B(X2,0.)
  350 GLP20X(J)=A(X2,Y2(20.),0.)
  360 GLM10X(J)=A(X2,Y2(-10.),0.)
  370 GLM20X(J)=A(X2,Y2(-20.),0.)
  380 GCTX(J)=A(X3(120.,RJ),Y3(120.,RJ),0.)
  390  GCTY(J)=B(X3(120.,RJ),0.)
  400 GCHX(J)=A(X3(1200.,RJ),Y3(1200.,RJ),0.)
  410  GCHY(J)=B(X3(1200.,RJ),0.)
  420 GCTHX(J)=A(X3(1.2E4,RJ),Y3(1.2E4,RJ),0.)
  430 GCTHY(J)=B(X3(1.2E4,RJ),0.)
  440 CH1X(J)=A(X4(201.9,RJ),Y3(201.9,RJ),0.)
```

```
 450 CH1Y(J)=B(X4(201.9,RJ),0.)
 460 CH2X(J)=A(X4(229.5,RJ),Y3(229.5,RJ),0.)
 470 CH2Y(J)=B(X4(229.5,RJ),0.)
 475 WRITE(6,495)PPLX(J),PPRX(J),PPLY(J),GLP10X(J),GLP20X(J),GLM10X(J),
 4801 GLM20X(J),GLP10Y(J),GCTX(J),GCTY(J)
 495  FORMAT(/,12E10.3)
 500 CONTINUE
 510 DO 600 J=1,181
 520 WRITE(6,550)GCHX(J),GCHY(J),GCTHX(J),GCTHY(J),CH1X(J),CH1Y(J),
 5301 CH2X(J),CH2Y(J)
 550 FORMAT(/,12E10.3)
 600 CONTINUE
795  STOP
 800 END
$        EXECUTE
$        LIMITS  04,30000,,100000
$        ENDJOB
```

APPENDIX G (continued) The Case 2 Program Listing is as follows:

```
$        IDENT    366,52120,2064B,72097,FILETTI
$        OPTION   FORTRAN
$        FORTRAN
      DIMENSION FWLSX(10),FWRSX(10),WMLSX(10),WMRSX(10),
     1                   .  PPLX(182),PPLY(182),PPRX(182),PPRY(182),
     2 GLP10X(182),GLP10Y(182),GLP20X(182),GLM10X(182),GLM20X(182),
     3 GC5X(182),GC5Y(182),GC10X(182),GC10Y(182),GC20X(182),GC20Y(182),
     4 GC30X(182),GC30Y(182),GC3HX(182),GC3HY(182),
     5 FWSY(10),WMSY(10)
   33 REAL N
   35 D(X,Z)=(C*X)+(S*Z)+(34.*S)
   40 N(X,Z)=(-S*X)+(C*Z)+(34.*C)
   45 A(X,Y,Z)=(8.20*4.*(Y/(D(X,Z))) )
   50 B(X,Z)=6.7-(8.20*4.*(N(X,Z))/(D(X,Z)))
   55 X3(R,X)=156.7+(R*(SIN((X-1.)*P)))
   60 X4(R,X)=(R*(SIN((X-1.)*P)))+4.
   70 Y3(R,X)=R*(COS((X-1.)*P))
   75 P=3.14159265/180.
   80 C=COS(5.*P)
   85 S=SIN(5.*P)
   90 DO 250 I=1,9
   95 RI=I
  105 FWSY(I)=B(147.7,0.)
  110 WMSY(I)=B(120.7,0.)
  130 FWLSX(I)=A(147.7,(-17.+RI),0.)
  140 FWRSX(I)=A(147.7,7.+RI,0.)
  150 WMLSX(I)=A(120.7,-17.+RI,0.)
  160 WMRSX(I)=A(120.7,7.+RI,0.)
  200 WRITE(6,210)FWLSX(I),FWRSX(I),FWSY(I),WMLSX(I),WMRSX(I),WMSY(I)
  210 FORMAT(/,12E10.3)
 250  CONTINUE
  260 DO 500 J=1,181
  270 RJ=J
  280 X5=156.7+((RJ)-1.)*(1.2**(RJ))
  290 PPLX(J)=A(X5,-12.,0.)
  300 PPLY(J)=B(X5,0.)
  310 PPRX(J)=A(X5,12.,0.)
  320 X2=156.7+((RJ)-1.)*(1.2**(RJ))
  330 GLP10X(J)=A((X2),Y2(10.),0.)
  340 GLP10Y(J)=B(X2,0.)
  350 GLP20X(J)=A(X2,Y2(20.),0.)
  360 GLM10X(J)=A(X2,Y2(-10.),0.)
  370 GLM20X(J)=A(X2,Y2(-20.),0.)
  380 GC5X(J)=A(X3(186.85,RJ),Y3(186.85,RJ),0.)
  385 GC5Y(J)=B(X3(186.85,RJ),0.)
  390 GC10X(J)=A(X3(393.7,RJ),Y3(393.7,RJ),0.)
  395 GC10Y(J)=B(X3(393.7,RJ),0.)
  400 GC20X(J)=A(X3(787.4,RJ),Y3(787.4,RJ),0.)
  405 GC20Y(J)=B(X3(787.4,RJ),0.)
  410 GC30X(J)=A(X3(1181.1,RJ),Y3(1181.1,RJ),0.)
  415 GC30Y(J)=B(X3(1181.1,RJ),0.)
  420 GC3HX(J)=A(X3(11811.,RJ),Y3(11811.,RJ),0.)
  430 GC3HY(J)=B(X3(11811.,RJ),0.)
  475 WRITE(6,495)PPLX(J),PPRX(J),PPLY(J),GLP10X(J),GLP20X(J),GLM10X(J),
 4801 GLM20X(J),GLP10Y(J),GC5X(J),GC5Y(J)
  495  FORMAT(/,12E10.3)
  500 CONTINUE
```

```
 510 DO 600 J=1,181
 520 WRITE(6,550)GC10X(J),GC10Y(J),GC20X(J),GC20Y(J),GC30X(J),
 5301 GC30Y(J),GC3HX(J),GC3HY(J)
 550 FORMAT(/,12E10.3)
 600 CONTINUE
795  STOP
 800 END
$      EXECUTE
$      LIMITS  04,30000,,100000
$      ENDJOB
```

APPENDIX G (continued) The Case 3 Program Listing is as follows:

```
$       IDENT    366,52120,2064B,72097,FILETTI
$       OPTION   FORTRAN
$       FORTRAN
      DIMENSION FWLSX(10),FWRSX(10),WMLSX(10),WMRSX(10),
     1                    PPLX(182),PPLY(182),PPRX(182),PPRY(182),
     3 GC5X(182),GC5Y(182),GC10X(182),GC10Y(182),GC20X(182),GC20Y(182),
     4 GC30X(182),GC30Y(182),GC3HX(182),GC3HY(182),
     5 FWSY(10),WMSY(10),
     6 R(8),GR07LX(182),GR07LY(182),GR15LX(182),GR15LY(182),GR22LX(182),
     7 GR22LY(182),GR30LX(182),GR30LY(182),GR07RX(182),GR07RY(182),
     8 GR15RX(182),GR15RY(182),GR22RX(182),GR22RY(182),GR30RX(182),
     9 GR30RY(182),GP07LX(150),GP07LY(150),GP07RX(150),GP07RY(150),
     A GP15LX(100),GP15LY(100),GP15RX(100),GP15RY(100),GP22LX(75),
     B GP22LY(75),GP22RX(75),GP22RY(75),GP30LX(50),GP30LY(50),
     C GP30RX(50),GP30RY(50)        ,ID(10),RID(8)
   33 REAL N
   35 D(X,Z)=(C*X)+(S*Z)+(34.*S)
   40 N(X,Z)=(-S*X)+(C*Z)+(34.*C)
   45 A(X,Y,Z)=(3.18*4.*(Y/(D(X,Z))))
   50 B(X,Z)=(5.-(3.18*4.*(N(X,Z))/(D(X,Z))))
   55 X3(R,X)=156.7+(R*(SIN((X-1.)*P)))
   60 X4(R,X)=(R*(SIN((X-1.)*P)))+4.
   70 Y3(R,X)=R*(COS((X-1.)*P))
   71 GRSX(X,Z)=147.7+X*SIN((Z-1.)*P)
   72 GRSY(X,Z)=X-X*COS((Z-1.)*P)
   73 GRSPX(X,Z)=147.7+X*SIN(Z*11.88/X)
   74 GRSPY(X,Z)=X-X*COS(Z*11.88/X)
   75 P=3.14159265/180.
   76 C=COS(12.5*P)
   77 S=SIN(12.5*P)
   81 R(1)=186.
   82 R(2)=97.5
   83 R(3)=64.
   84 R(4)=51.
   85 R(5)=216.
   86 R(6)=106.5
   87 R(7)=69.5
   88 R(8)=54.
   89 WRITE(6,90)
   90 FORMAT(1H,3X,5HFWLSX,5X,5HFWRSX,5X,4HFWSY,6X,5HWMLSX,5X,5HWMRSX,
   92 DO 250  I=1,9
   95 RI=I
  105 FWSY(I)=B(147.7,0.)
  110 WMSY(I)=B(120.7,0.)
  130 FWLSX(I)=A(147.7,(-17.+RI),0.)
  140 FWRSX(I)=A(147.7,7.+RI,0.)
  150 WMLSX(I)=A(120.7,-17.+RI,0.)
  160 WMRSX(I)=A(120.7,7.+RI,0.)
  200 WRITE(6,210)FWLSX(I),FWRSX(I),FWSY(I),WMLSX(I),WMRSX(I),WMSY(I)
  210 FORMAT(/,12E10.3)
 250  CONTINUE
  252 WRITE(6,254)
  254 FORMAT(1H,3X,4HPPLX,6X,4HPPRX,6X,4HPPLY,6X,6HGLP10X,4X,
  2551 6HGLP20X,4X,6HGLM10X,4X,6HGLM20X,4X,6HGLP10Y,4X,4HGC5X,6X,4HGC5Y)
  260 DO 500  J=1,181
  270 RJ=J
  280 X5=156.7+((RJ)-1.)*(1.2**(RJ))
```

```
290 PPLX(J)=A(X5,-12.,0.)
300 PPLY(J)=B(X5,0.)
310 PPRX(J)=A(X5,12.,0.)
380 GC5X(J)=A(X3(186.85,RJ),Y3(186.85,RJ),0.)
385 GC5Y(J)=B(X3(186.85,RJ),0.)
390 GC10X(J)=A(X3(393.7,RJ),Y3(393.7,RJ),0.)
395 GC10Y(J)=B(X3(393.7,RJ),0.)
400 GC20X(J)=A(X3(787.4,RJ),Y3(787.4,RJ),0.)
405 GC20Y(J)=B(X3(787.4,RJ),0.)
410 GC30X(J)=A(X3(1181.1,RJ),Y3(1181.1,RJ),0.)
415 GC30Y(J)=B(X3(1181.1,RJ),0.)
420 GC3HX(J)=A(X3(11811.,RJ),Y3(11811.,RJ),0.)
430 GC3HY(J)=B(X3(11811.,RJ),0.)
475 WRITE(6,495)PPLX(J),PPRX(J),PPLY(J),
4801                         GC5X(J),GC5Y(J)
495  FORMAT(/,12E10.3)
500 CONTINUE
502 WRITE(6,504)
504 FORMAT(1H,3X,5HGC10X,5X,5HGC10Y,5X,5HGC20X,5X,5HGC20Y,5X,5HGC30X,
5051 5X,5HGC30Y,5X,5HGC3HX,5X,5HGC3HY)
510 DO 600 J=1,181
520 WRITE(6,550)GC10X(J),GC10Y(J),GC20X(J),GC20Y(J),GC30X(J),
5301 GC30Y(J),GC3HX(J),GC3HY(J)
550 FORMAT(/,12E10.3)
600 CONTINUE
610 WRITE (6,620)
620 FORMAT(1H,3X,6HGR07LX,4X,6HGR07LY,4X,6HGR07RX,4X,6HGR07RY,4X,
   1 6HGR15LX,4X,6HGR15LY,4X,6HGR15RX,4X,6HGR15RY,4X,6HGR22LX,4X,
   2 6HGR22LY,4X,6HGR22RX,4X,6HGR22RY)
650 DO  850   K= 1,181
660 RK=K
670 GR07LX(K)=A(GRSX(R(1),RK),-GRSY(R(1),RK),0.)
680 GR07LY(K)=B(GRSX(R(1),RK),0.)
690 GR15LX(K)=A(GRSX(R(2),RK),-GRSY(R(2),RK),0.)
700 GR15LY(K)=B(GRSX(R(2),RK),0.)
710 GR22LX(K)=A(GRSX(R(3),RK),-GRSY(R(3),RK),0.)
720 GR22LY(K)=B(GRSX(R(3),RK),0.)
730 GR30LX(K)=A(GRSX(R(4),RK),-GRSY(R(4),RK),0.)
740 GR30LY(K)=B(GRSX(R(4),RK),0.)
750 GR07RX(K)=A(GRSX(R(5),RK),GRSY(R(5),RK),0.)
760 GR07RY(K)=B(GRSX(R(5),RK),0.)
770 GR15RX(K)=A(GRSX(R(6),RK),GRSY(R(6),RK),0.)
780 GR15RY(K)=B(GRSX(R(6),RK),0.)
790 GR22RX(K)=A(GRSX(R(7),RK),GRSY(R(7),RK),0.)
800 GR22RY(K)=B(GRSX(R(7),RK),0.)
810 GR30RX(K)=A(GRSX(R(8),RK),GRSY(R(8),RK),0.)
820 GR30RY(K)=B(GRSX(R(8),RK),0.)
830 WRITE(6,840)GR07LX(K),GR07LY(K),GR07RX(K),GR07RY(K),GR15LX(K),
8311 GR15LY(K),GR15RX(K),GR15RY(K),GR22LX(K),GR22LY(K),GR22RX(K),
8322 GR22RY(K)
840 FORMAT(/,12E10.3)
850 CONTINUE
860 WRITE(6,865)
865 FORMAT(1H,3X,6HGR30LX,4X,6HGR30LY,4X,6HGR30RX,4X,6HGR30RY)
870 DO  890   K=1,181
875 WRITE(6,880)GR30LX(K),GR30LY(K),GR30RX(K),GR30RY(K)
880 FORMAT(/,12E10.3)
```

```
890 CONTINUE
900 WRITE(6,905)
905 FORMAT(1H,3X,4HD(1),6X,4HD(2),6X,4HD(3),6X,4HD(4),6X,4HD(5),6X,
9061 4HD(6),6X,4HD(7),6X,4HD(8))
910 DO 920  J=1,8
915 ID(J)= INT(360.*P*R(J)/11.88)
917 RID(J)=ID(J)
920 CONTINUE
925 WRITE(6,930)RID(1),RID(2),RID(3),RID(4),RID(5),RID(6),
9261 RID(7),RID(8)
930 FORMAT(/,12E10.3)
935 WRITE(6,940)
940 FORMAT(1H,3X,6HGP07LX,4X,6HGP07LY)
942 ID1=ID(1)
945 DO 985 J=1,ID1
950 RJ=J
955 GP07LX(J)=A(GRSPX(R(1),RJ),-GRSPY(R(1),RJ),0.)
960 GP07LY(J)=B(GRSPX(R(1),RJ),0.)
970 WRITE(6,980)GP07LX(J),GP07LY(J)
980 FORMAT(/,12E10.3)
985 CONTINUE
990 WRITE(6,995 )
995 FORMAT(1H,3X,6HGP07RX,4X,6HGP07RY)
997 ID5=ID(5)
1000 DO 1030 J=1,ID5
1005 RJ=J
1010 GP07RX(J)=A(GRSPX(R(5),RJ),GRSPY(R(5),RJ),0.)
1015 GP07RY(J)=B(GRSPX(R(5),RJ),0.)
1020 WRITE(6,1025)GP07RX(J),GP07RY(J)
1025 FORMAT(/,12E10.3)
1030 CONTINUE
1035 WRITE(6,1040)
1040 FORMAT(1H,3X,6HGP15LX,4X,6HGP15LY)
1042 ID2=ID(2)
1045 DO 1075 J=1,ID2
1050 RJ=J
1055 GP15LX(J)=A(GRSPX(R(2),RJ),-GRSPY(R(2),RJ),0.)
1060 GP15LY(J)=B(GRSPX(R(2),RJ),0.)
1065 WRITE(6,1070)GP15LX(J),GP15LY(J)
1070 FORMAT(/,12E10.3)
1075 CONTINUE
1080 WRITE(6,1085)
1085 FORMAT(1H,3X,6HGP15RX,4X,6HGP15RY)
1087 ID6=ID(6)
1090 DO 1120 J=1,ID6
1095 RJ=J
1100 GP15RX(J)=A(GRSPX(R(6),RJ),GRSPY(R(6),RJ),0.)
1105 GP15RY(J)=B(GRSPX(R(6),RJ),0.)
1110 WRITE(6,1115)GP15RX(J),GP15RY(J)
1115 FORMAT(/,12E10.3)
1120 CONTINUE
1125 WRITE(6,1130)
1130 FORMAT(1H,3X,6HGP22LX,4X,6HGP22LY)
1132 ID3=ID(3)
1135 DO 1165 J=1,ID3
1140 RJ=J
1145 GP22LX(J)=A(GRSPX(R(3),RJ),-GRSPY(R(3),RJ),0.)
```

```
1150 GP22LY(J)=B(GRSPX(R(3),RJ),0.)
1155 WRITE(6,1160)GP22LX(J),GP22LY(J)
1160 FORMAT(/,12E10.3)
1165 CONTINUE
1170 WRITE(6,1175)
1175 FORMAT(1H,3X,6HGP22RX,4X,6HGP22RY)
1177 ID7=ID(7)
1180 DO 1210 J=1,ID7
1185 RJ=J
1190 GP22RX(J)=A(GRSPX(R(7),RJ),GRSPY(R(7),RJ),0.)
1195 GP22RY(J)=B(GRSPX(R(7),RJ),0.)
1200 WRITE(6,1205)GP22RX(J),GP22RY(J)
1205 FORMAT(/,12E10.3)
1210 CONTINUE
1215 WRITE(6,1220)
1220 FORMAT(1H,3X,6HGP30LX,4X,6HGP30LY)
1222 ID4=ID(4)
1225 DO 1255 J=1,ID4
1230 RJ=J
1235 GP30LX(J)=A(GRSPX(R(4),RJ),-GRSPY(R(4),RJ),0.)
1240 GP30LY(J)=B(GRSPX(R(4),RJ),0.)
1245 WRITE(6,1250)GP30LX(J),GP30LY(J)
1250 FORMAT(/,12E10.3)
1255 CONTINUE
1260 WRITE(6,1265)
1265 FORMAT(1H,3X,6HGP30RX,4X,6HGP30RY)
1267 ID8=ID(8)
1270 DO 1300 J=1,ID8
1275 RJ=J
1280 GP30RX(J)=A(GRSPX(R(8),RJ),GRSPY(R(8),RJ),0.)
1285 GP30RY(J)=B(GRSPX(R(8),RJ),0.)
1290 WRITE(6,1295)GP30RX(J),GP30RY(J)
1295 FORMAT(/,12E10.3)
1300 CONTINUE
2000 CALL PLOTE(10.)
2005 CALL PLT(FWLSX,FWSY,9)
2020 CALL PLT(FWRSX,FWSY,9)
2030 CALL PLT(WMLSX,WMSY,9)
2040 CALL PLT(WMRSX,WMSY,9)
2050 CALL PLT(PPLX,PPLY,181)
2060 CALL PLT(PPRX,PPLY,181)
2200 CALL PLT(GR07LX,GR07LY,181)
2210 CALL PLT(GR15LX,GR15LY,181)
2220 CALL PLT(GR22LX,GR22LY,181)
2230 CALL PLT(GR30LX,GR30LY,181)
2240 CALL PLT(GR07RX,GR07RY,181)
2250 CALL PLT(GR15RX,GR15RY,181)
2260 CALL PLT(GR22RX,GR22RY,181)
2270 CALL PLT(GR30RX,GR30RY,181)
2280 CALL PLT(GC5X,GC5Y,181)
2290 CALL PLT(GC10X,GC10Y,181)
2300 CALL PLT(GC20X,GC20Y,181)
2310 CALL PLT(GC30X,GC30Y,181)
2320 CALL PLT(GC3HX,GC3HY,181)
2500 CALL PLOTE(15.)
3000 STOP
3100 END
```

```
$       FORTRAN DECK
CPLT
1000   SUBROUTINE PLT(X,Y,N)
1010   DIMENSION X(1),Y(1)
 1020 XMIN=-6.35
 1030 XMAX=6.35
1040   YMIN=0.
1050   YMAX=10.
1070   DO 1150 I=1,N
1080   IF(X(I).LT.XMIN.OR.X(I).GT.XMAX)GO TO 1150
1090   IF(Y(I).LT.YMIN.OR.Y(I).GT.YMAX) GO TO 1150
1095   IF(I.EQ.1)GO TO 1140
1100   IF(X(I-1).LT.XMIN.OR.X(I-1).GT.XMAX)GO TO 1140
1110   IF(Y(I-1).LT.YMIN.OR.Y(I-1).GT.YMAX)GO TO 1140
1120   CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-2)
1130   GO TO 1150
1140   CALL SYMBOL(X(I),Y(I),1.E-3,0,0.,-1)
1150   CONTINUE
1160   RETURN
1170   END
$       EXECUTE
$       LIMITS  04,30000,,100000
$       ENDJOB
```